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TORUS: Theory of Reactions for Unstable iSotopes - Topical Collaboration for Nuclear Theory Project. Period: June 1, 2010 - May 31, 2015

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TORUS:
Theory of Reactions for Unstable iSotopes

A Topical Collaboration for Nuclear Theory
Project Period: June 1, 2010 – May 31, 2015

Final Report
August 2015

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1 Introduction

Background

The TORUS collaboration derived its name from the research it focuses on, namely the **T**heory **o**f **R**eactions for **U**nstable i**S**otopes. It was a Topical Collaboration in Nuclear Theory, and funded by the Nuclear Theory Division of the Office of Nuclear Physics in the Office of Science of the Department of Energy. The funding supported one postdoctoral position for the years 1 through 4, and also a student. The collaboration brought together as Principal Investigators a large fraction of the nuclear reaction theorists currently active within the USA.

Mission

The mission of the TORUS Topical Collaboration was to develop new methods that advance nuclear reaction theory for unstable isotopes by using three-body techniques to improve direct-reaction calculations. This multi-institution collaborative effort was and remains directly relevant to three areas of interest: the properties of nuclei far from stability; microscopic studies of nuclear input parameters for astrophysics, and microscopic nuclear reaction theory.

Highlights from the Collaboration

1. 50 papers published in 5 years – Section 5.
2. 99 presentations, including invited talks at various national and international venues, such as the European Conference on Few-Body Problems in Physics – Section 5.2.
3. Organization of 5 workshops, including the two-week INT workshop "Reactions and Structure of Exotic Nuclei" in March 2015 – Section 5.3.
4. Benchmarked the Continuum Discretized Coupled Channel (CDCC) method against the current implementation of the Faddeev AGS method (FAGS): Uphadhyay, Nunes and Deltuva, Phys. Rev. C **85**, 054621 (2012).
5. Implementation of the Coulomb distorted nuclear form factors: Upadhyay et al., Phys. Rev. C **90**, 014615 (2014)
6. Developed a stand-alone code for partial wave Coulomb wave functions in momentum space: Eremenko, Upadhyay, et al., Computer Physics Communications, **187**, 195 (2015)
7. The development of separable optical potentials: Hlophe et al., Phys. Rev C. **90**, 061602 (2014); Phys. Rev C 88, 064608 (2013).
8. Development and implementation of Surface Operator method for transfer reactions: Mukhamedzhanov et al., Phys. Rev. C, **84** (2011), 044616; Escher et al, Phys. Rev. **C89** (2014), 054605
9. Coupled-channels combination of isobaric analog and semidirect mechanisms for neutron capture: Thompson et al., Nuclear Data Sheets, **118** (2014), 292; **118** (2014), 298.

2 Research

2.1 Overview

The task of the Topical Collaboration on the Theory of Reactions for Unstable iSotopes (TORUS) has been to develop new methods to advance nuclear reaction theory for unstable isotopes, particularly the (d,p) reaction in which a deuteron, composed of a proton and a neutron, transfers its neutron to an unstable nucleus. These reactions will be particularly useful at FRIB for probing the properties of new isotopes and their role in the neutron-capture reactions. All the new machinery being developed in this project are essential ingredients in applications of nuclear measurements for astrophysics, energy production, and national security applications. The TORUS project focused on understanding the details of (d,p) reactions for neutron transfer to heavier nuclei.

The first stage of TORUS work was to characterize the long-suspected shortcomings of previous methods in reaction theory. The background is that previous first-order theories, to be valid at all beam energies, need to be extended [49, 48, 51] to coupled-channels theories (CDCC) to describe deuteron breakup [10, 9], but even CDCC models have trouble with energy-dependent and non-local optical potentials [47, 78, 22, 52, 73] and with bound states in rearrangement channels.

TORUS work found [50, 74] that, after benchmarking these methods alongside state-of-the-art Faddeev theories, there were no exact methods available to study (d,p) reactions involving heavy targets; the difficulty arising from the long-range nature of the well known, yet subtle, Coulomb force. To meet this challenge, the TORUS collaboration developed a new Faddeev theory [44], in which the complexity of treating the long-range Coulomb interaction explicity is shifted to evaluating Coulomb distorted matrix elements instead. We showed how to explicitly calculate those matrix elements in momentum space for complex optical potentials [75], derived those potentials in the required representation for neutrons [31] and protons [32], and developed an efficient computational method for Coulomb functions in momentum space [23]. These methods can be used for scattering of both neutrons and protons [20], and can include the details and energy dependence of modern optical potentials.

The (d,p) reactions add a neutron to a nucleus to give structures very similar to that resulting from (n,γ) capture reactions of great interest to astrophysics and other applications. TORUS work examined how the two channels may possibly give different results from two-step effects [69], from isobaric analog transitions [68], few-body dynamics in the entrance channel [46], and the interplay between direct and statistical contributions [80, 38]. We also examined carefully the relation between these model predictions and the measurable properties of nuclear states [43, 72, 42], in particular seeking to describe (d,p) cross sections as much as possible in terms of the measurable surface properties of neutrons in both bound and resonant states [41, 25, 26].

We worked additionally with experimentalists on many projects for both discrete [37, 40, 15, 64, 39, 30, 63, 67] and statistical final states [34, 59, 62, 33, 79, 54, 53]. We have published multiple articles that review progress in reaction theory [19, 50, 71, 11, 77, 4, 5].

One postdoctoral collaborator, N. Upadhyay, went to a research position at Lousiana State University and then to India, while V. Eremenko will go to a staff position at Moscow State University.

All citations in [square brackets] are to our own collaborations, as listed in the References from page 41.

2.2 Coupled-channel Theory

2.2.1 Distinguishing peripheral, surface, and interior contributions

J.E. Escher and I.J. Thompson, in collaboration with the Texas A&M Group

A major motivation for our work originates from the new opportunities that rare isotope facilities offer now and in the future. It is therefore essential to clearly identify what can and cannot be measured in current and upcoming experiments. In this context we have investigated whether, and under which circumstances, transfer reactions probe the nuclear interior or the surface. We have carried out studies for bound as well as resonance final states, as both types are important for extracting information that can be used to constrain nuclear structure models.

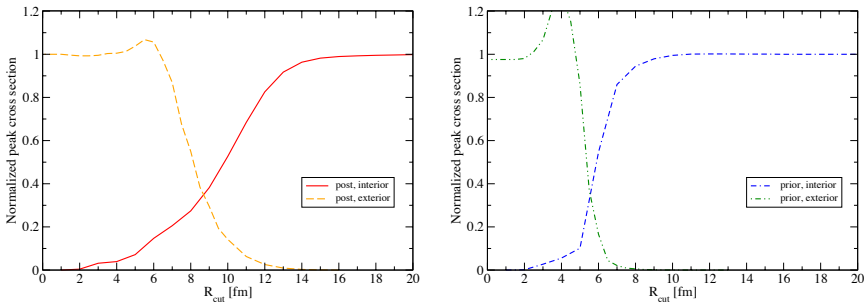

Figure 1: Examination of the role of interior, exterior, and surface contributions for ^{90}Zr(d,p)^{91}Zr stripping to the ground state. The two panels give the contributions of the interior, $M(0,a)$, and exterior, $M(a,\infty)$, transition amplitudes to the cross section, in post (left) and prior (right) form.

In order to identify which parts of the nucleus are probed by transfer reactions, we have examined the relative interior and exterior contributions of the reaction amplitude to calculated transfer cross sections. We investigate the individual contributions from the internal and external parts of the reaction amplitude, where internal and external is defined in terms of the distance r_{nA} between the transferred neutron and the target. DWBA calculations were carried out for a range of targets, ^{12}C, ^{16}O, ^{20}O, ^{40}Ca, ^{48}Ca, ^{90}Zr, and ^{208}Pb, for incident deuteron energies between 11 and 82 MeV. An example, for ^{90}Zr(d,p)^{91}Zr is shown in Fig. 1. Our main finding is that, although the post and prior DWBA amplitudes are equal, their behavior is quite different in the subspace over the variable r_{nA}. The prior formulation is clearly more sensitive to the nuclear interior (and thus to model assumptions about the interior structure), while contributions from the peripheral part of the $n+$ target system dominate the post form [25]. These insights are relevant as they point to strategies for developing reaction descriptions with reduced dependence on a model for the nuclear interior. One such strategy is employed in the surface integral formalism, developed by A. Mukhamedzhanov [41] and explored in more detail in the study described next.

2.2.2 Surface contributions for first-order transfers to bound and resonance states

J.E. Escher and I.J. Thompson

An important goal of reaction theory is to address shortcomings in the description of transfers to resonance states. Resonance states play crucial roles in our understanding of nuclear structure and in astrophysical applications. Current descriptions of transfer reactions that populate resonances suffer from major shortcomings, including numerical convergence issues and conceptual

questions regarding what spectroscopic information can be extracted from experimental observables. The surface integral formalism, introduced by A. Mukhamedzhanov [41], was developed to address these issues. The surface-integral method builds on ideas from the very successful R-matrix theory; it uses a similar separation of the parameter space into interior and exterior regions, and introduces a parameterization that can be related to physical observables, which, in principle, makes it possible to extract meaningful spectroscopic information from experiments. The reaction amplitude is recast in terms of a surface integral plus remnant terms that contain contributions from the interior and exterior of the final nucleus, where interior and exterior are defined with respect to the distance r_{nA} between the transferred nucleon and the target nucleus: $M^{(DWBA)} = M_{\rm int}^{(post)}(0,a) + M_{\rm surf}(a) + M_{\rm ext}^{(prior)}(a,\infty)$. The notation $M(x,y)$ indicates the lower (x) and upper (y) limits of the integration over r_{nA}, and the surface term is evaluated at $r_{nA} = a$; 'post' and 'prior' refer to the standard post and prior formalisms used in transfer calculations. The interior post term is model-dependent, while the exterior prior and surface terms are related to the asymptotic properties of the wave function. These statements apply to both the DWBA framework and the CDCC (Continuum-Discretized Coupled-Channels) framework, where the latter allows for simultaneous treatment of the breakup channel.

We studied the contributions from the interior-post, surface, and exterior-prior terms to the (d,p) cross sections for several target nuclei in the DWBA framework. In all cases, for both bound and resonance final states, we found that the surface term gives the dominant contributions, provided a separation radius is chosen that is in the region of the nuclear surface. When comparing to exact calculations of the cross sections, however, we also found that significant strength is missing (30-50%), which indicates that the residual terms cannot be neglected. In the region where the surface cross section peaks, we found contributions from both the interior-post and the exterior-prior terms.

We identified a path forward for practical applications of the surface-integral formalism. We considered a separation radius a that is slightly smaller than the radius corresponding to the peak of the surface term. This minimizes contributions from the post-interior term, thus removing the need for a model for the one-nucleon overlap function in the nuclear interior. With a decrease in the surface radius comes an increase in the contribution from the prior-exterior term, making it necessary to including this term explicitly. We illustrate the effect in Figure 2, where we consider a $3/2^+$ resonance at 4.77 MeV in ^{21}O. The surface cross section shown in panel b) was calculated with separation radius $a = 5.0$ fm, which corresponds to the maximum of the surface contribution. The curve falls clearly short of reproducing the full cross section. Also shown is a calculation that contains both surface and prior-exterior contributions. We observe a slight improvement in the agreement with the exact calculation, but additional contributions (from the post-interior term) would be needed to achieve satisfactory agreement.

Moving the separation radius to smaller values, however, improves the situation, as a comparison between panels a) and b) demonstrates. In panel a) we show analogous surface-only and surface-plus-interior-prior calculations, but for a radius that is 0.5 fm smaller than in panel b). While this shift in a reduces the surface-only cross section, it increases the cross section arising from the the exterior-prior term, with the sum giving a much better approximation to the exact cross section. Similar results were found for a $3/2^+$ and a $7/2^-$ resonance at 6.17 MeV.

Our findings [26] point to possible improvements of the surface-integral approach when implemented in the continuum-discretized coupled-channels (CDCC) framework [3]. A successful implementation of the approach, as in the next section, will be significant for the description of transfers to resonances, as the surface integral term can be expressed in terms of resonance prop-

erties (energies and widths).

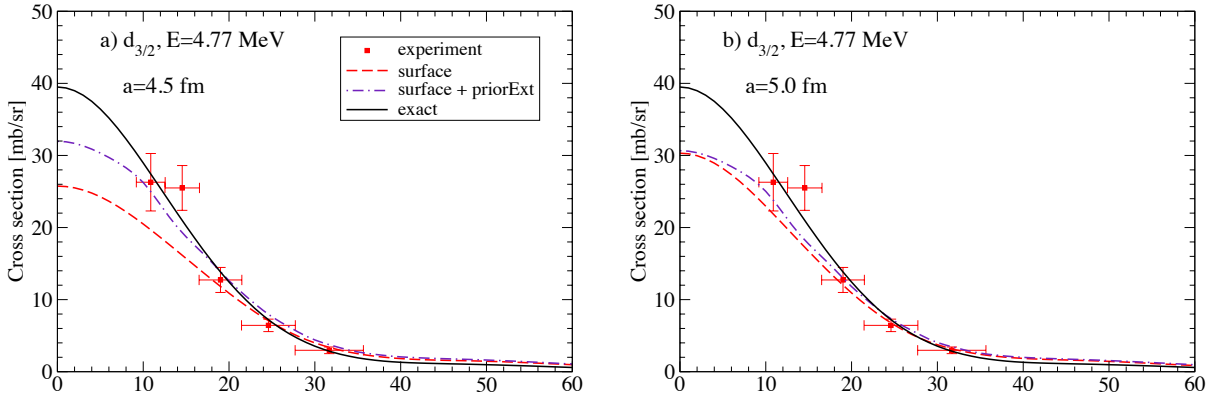

Figure 2: Surface-integral description of one-nucleon transfer to a $3/2^+$ resonance in ^{21}O. Improvements to the surface-term-only approximation can be achieved by including contributions from the prior-exterior term and selecting a small surface radius. Shown are the surface-only results (dashed curve) and the surface plus interior-prior results (dash-dotted curve), compared to the full calculation (solid line) and to experiment. The calculations in panel b) were carried out at a surface radius $a = 5.0$ fm that coincides with the maximum of the surface term, and panel a) shows the effect of reducing a by 0.5 fm. The cross section arising from the surface term decreases, while the cross section associated with the sum of the surface and the prior-exterior term shows improved agreement with the exact results.

2.2.3 Surface operator for transfers after breakup

I.J. Thompson and J.E. Escher, in collaboration with the Texas A&M Group

The surface contributions extracted in the previous section are within the context of first-order theory, as then post and prior matrix elements give identical results and differences can be taken. If breakup in the entrance channel, say, is important, then it is necessary to go beyond first order. In that case, only the post matrix element use the coupled-channels wave function in the entrance channel from the CDCC methods discussed earlier. This means that the surface operator has to be calculated explicitly in terms of the multi-channel CDCC wave functions $\psi_{\rm CDCC}(\vec{R},\vec{r})$. This we have implemented, and have shown how to go beyond first order for neutron transfers both to bound and resonance states.

The source terms for the outgoing transfer channel in a (d,p) reaction that need to be calculated are of the form

$$S_\beta^{\rm surf}(R') = -\frac{\hbar^2}{2\mu_n}\int_0^\infty dr' \left\langle Y_\beta(\hat{R}',\hat{r}')\middle|\delta(r'-\rho)\left[\frac{\partial\Phi_\beta(r')}{\partial r'} - \Phi_\beta(r')\frac{\partial}{\partial r'}\right]\middle|\psi_{\rm CDCC}(\vec{R},\vec{r})\right\rangle \qquad (1)$$

where r' is the coordinate of the neutron in the final state, R' that of the exit proton, and $r' = \rho$ defines the radius of the surface. Since the derivative operator $\partial/\partial r'$ acts on both the radial and angular components of the vectors $(\vec{R},\vec{r})$ in the entrance channel, a large number of terms and

derivatives need to be evaluated:

$$S^{\rm surf}_{\beta\alpha}(R') = -\frac{\hbar^2}{2\mu_n}\sum_{M'_L m'_\ell M_L m_\ell} F_\beta^{M'_L m'_\ell:M*} C_\alpha^{M_L m_\ell:M} \langle Y_{L'}^{M'_L}(\hat{\mathbf{R}}')\; Y_{\ell'}^{m'_\ell}(\hat{\mathbf{r}}')|_{r'=\rho}\frac{1}{rR}$$

$$\Bigg[\Phi'_\beta(\rho)\;\; Y_\ell^{m_\ell}(\hat{\mathbf{r}})\, Y_L^{M_L}(\hat{\mathbf{R}}) \quad \varphi_\alpha(r)\, u_\alpha(R)$$

$$- \Phi_\beta(\rho)\Bigg(Y_L^{M_L}(\hat{\mathbf{R}}) u_\alpha(R) p\Bigg\{ \frac{\varphi_\alpha(r)}{r}\sqrt{\frac{4\pi\ell(2\ell{+}1)}{3}}\sum_{\lambda=-1}^{1}\langle \ell{-}1\; m{-}\lambda, 1\lambda|\ell m\rangle Y_{\ell-1}^{m-\lambda}(\hat{\vec{r}}) Y_1^\lambda(\hat{\vec{r}'})$$

$$+ Y_\ell^m(\hat{\mathbf{r}})\;\hat{\mathbf{r}}\cdot\hat{\mathbf{r}'}\left[\varphi'_\alpha(r) - \frac{\ell{+}1}{r}\varphi_\alpha(r)\right]\Bigg\}$$

$$+ Y_\ell^{m_\ell}(\hat{\mathbf{r}})\varphi_\alpha(r) P\Bigg\{\sqrt{\frac{4\pi L(2L{+}1)}{3}}\sum_{\Lambda=-1}^{1}\langle L{-}1\; M_L{-}\Lambda, 1\Lambda|LM_L\rangle Y_{L-1}^{M_L-\Lambda}(\hat{\vec{R}}) Y_1^\Lambda(\hat{\vec{r}'})\frac{u_\alpha(R)}{R}$$

$$+ Y_L^{M_L}(\hat{\mathbf{R}})\;\hat{\mathbf{R}}\cdot\hat{\mathbf{r}'}\left[u'_\alpha(R) - \frac{L{+}1}{R}u_\alpha(R)\right]\Bigg\}\quad\Bigg)\Bigg]\,. \tag{2}$$

These are evaluated in the rotated coordinate frame that has the z-axis parallel to $\mathbf{R}$ and the x-axis in the plane of $\mathbf{R}$ and $\mathbf{R}'$. The resulting operator is still non-local like other finite-range transfer operators, but does not require any internal quadrature over angles. Furthermore, its value depends only on the wave function $\Phi_\beta(\rho)$ and derivative $\Phi'_\beta(\rho)$ of the final neutron wave function on the surface, and these are precisely the numbers that can be uniquely obtained from standard R-matrix fits of pole positions and reduced-width amplitudes.

Nevertheless, as shown in the previous section, the internal post terms are still significant and need to be added coherently to the surface contributions. Figure 3 shows the relative sizes of these terms for a ^{20}O(d,p)^{21}O reaction that populates a d-wave neutron resonance at 0.9 MeV. The different panels show the effects of different radii of the surface, where the black curve shows the surface term, the red-dotted line the interior post by itself, and the green curve shows their coherent sum. Except for the smallest surface radius, the coherent sums are nearly constant, but there are large variations in the relative sizes of the surface and interior-post terms. This will provide an essential tool for probing how much these transfer cross sections measure the surface properties described by R-matrix theory, compared with measuring in part the interior part of the resonance wave functions.

2.2.4 Breakup and transfer within CDCC

Upadhyay and Nunes, in collaboration with Deltuva

One of the most well established theories for direct nuclear reactions is the Continuum Discretized Coupled Channels (CDCC) method. It includes breakup to all orders by discretizing the projectile continuum into bins. Alternatively, the 3-body problem can be solved exactly within the Faddeev momentum space integral formalism (here denoted FAGS) which explicitly includes breakup and transfer channels to all orders.

With the aim of quantifying the accuracy of CDCC in computing elastic, breakup and transfer

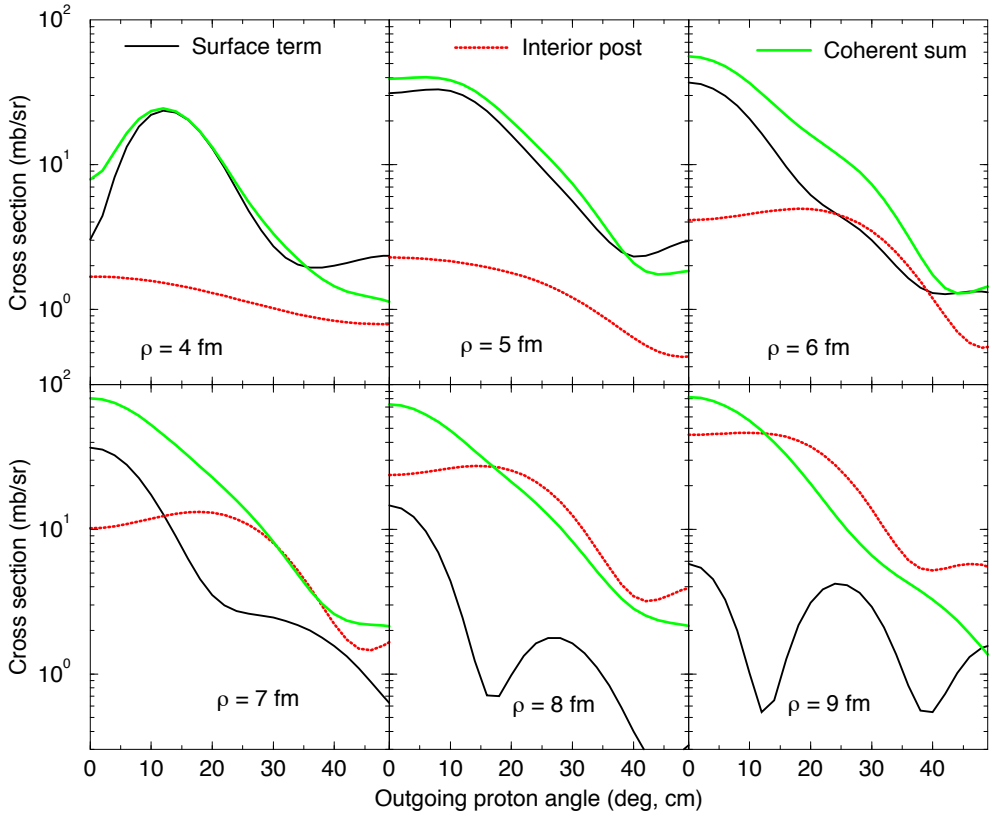

Figure 3: The cross sections from separate surface and interior-post terms (black and red respectively) along with their coherent sum (green line). The different panels show the variations from using different radii ρ of the surface.

cross sections and establish a range of validity, we completed a systematic comparison of CDCC and Faddeev. Our test cases consist of: i) d+^{10}Be at $E_{\rm d} = 21.4, 40.9$ and 71 MeV; ii) d+^{12}C at $E_{\rm d} = 12$ and 56 MeV; and iii) d+^{48}Ca at $E_{\rm d} = 56$ MeV. These reactions were chosen to match available experimental data however the goal of the project was to understand the limitations of CDCC and therefore no fine tuning of interactions was performed. This work has been published [74]. As we summarize below, our results pose important constraints on the validity of CDCC when applied to deuteron induced reactions, as well as the current implementation of FAGS, and call for a better description of the reaction dynamics.

We compute elastic scattering, transfer cross sections to the ground state of the final system, as well as breakup observables. In CDCC, elastic scattering and breakup cross sections are obtained directly from the S-matrix, while transfer is calculated replacing the exact three-body wavefunction by the CDCC wavefunction in the exact post-form T-matrix.

Our CDCC/FAGS comparisons show no immediate correlation between elastic, transfer or breakup. In other words, finding agreement for the elastic for a given target and beam energy does not imply agreement in breakup or transfer. Indeed, these processes are sensitive to different parts of configuration space and therefore, only by looking at elastic, transfer and breakup simultaneously, can the CDCC method be thoroughly tested.

Overall, and regardless of the beam energy, CDCC is able to provide a good approximation

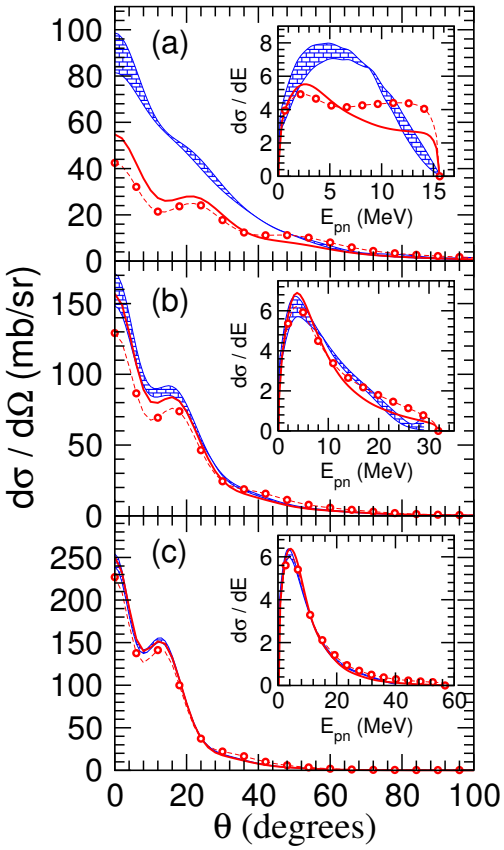

Figure 4: Breakup distributions for ^{10}Be (d, pn) ^{10}Be reaction at: (a) $E_{\rm d}$ = 21 MeV, (b) $E_{\rm d}$ = 40.9 MeV and (c) $E_{\rm d}$ = 71 MeV. Results for CDCC (hashed bar), FAGS(solid) and FAGS1 (circles).

to FAGS for *elastic* scattering. The inclusion of a neutron-nucleus bound state in the FAGS1 calculations [74] introduces small modifications mostly at backward angles. Only for d+^{12}C at 12 MeV we found stronger discrepancies in the elastic angular distribution between CDCC and Faddeev-AGS.

The comparison of CDCC and Faddeev-AGS for *transfer* cross sections is consistent with the results presented in [48]. We found CDCC to be a very good approximation of FAGS1 at reactions around 10 MeV/u, but not so good for larger beam energies. What became clear from our study is that, for loosely bound s-wave dominated projectiles, CDCC does not improve the description of transfer when compared to the adiabatic model (ADWA). Because CDCC is computationally expensive, ADWA should be the preferred tool. Why, at larger beam energies, CDCC is not able to improve the description of breakup when compared to ADWA has to do with the fact that at higher energies the adiabatic approximation works very well.

Breakup observables predicted by CDCC are at its best for the higher beam energies explored in this work. To reduce the technical challenges of the problem, we ignore the Coulomb interaction in the breakup comparison. Also, we use exactly the same Hamiltonian (CDCC and FAGS) to remove any ambiguity.

In Fig.4 we present the results for the angular distribution as a function of the c.m. angle of the pn system following the breakup on ^{10}Be at the three energies of choice. At the lowest energy, we find that CDCC does not reproduce FAGS, even taking into account the error estimated by model space truncation. At the higher energies, this discrepancy is removed. The insets of Fig.4

contain the corresponding energy distributions as functions of the proton-neutron relative energy E_{pn}. Again, a very large discrepancy is found at 21.4 MeV while fair agreement between CDCC and FAGS is obtained at the higher energies.

Similar conclusions can be drawn from the comparison of breakup angular and energy distributions for reactions on ^{12}C. Despite the large error bar in the CDCC predictions, there is a striking mismatch between CDCC and FAGS in both magnitude and shape of the breakup cross sections at 12 MeV. These discrepancies disappear at the higher energy. Agreement is obtained between CDCC and FAGS for the breakup of deuterons on ^{48}Ca at 56 MeV.

Although the calculations themselves represent a challenge, understanding the reason for the differences turns out to be even more challenging. We explored the effects of including the nA bound state in the transfer channel with FAGS1 (dotted circles). By comparing FAGS and FAGS1 we conclude that the effects of transfer are not negligible on breakup, particularly at low energies.

In addition we looked at the various components in the Faddeev approach. Strong contributions from the proton and neutron Faddeev components, not explicitly included in the CDCC expansion, are present when the proton-neutron relative energies are large. At low energy, the energy distribution is broad, the breakup to scattering states with large proton-neutron relative energy is important and therefore CDCC does not perform well. One possible solution to this shortcoming may be to use the CDCC wavefunction in a T-matrix that probes only short distances between the proton and neutron, instead of its asymptotic form.

2.3 Modeling (d,p) reactions with a Faddeev-AGS approach

In this subsection, the work on the few-body Faddeev-AGS approach to (d, p) reactions is described. One of the most challenging aspects of solving the three-body problem for nuclear reactions is the repulsive Coulomb interaction. While the Coulomb interaction for very light nuclei is often a small correction to the problem, this is certainly not the case for intermediate mass and heavy systems. At the start of the TORUS work, the most complete implementation of a Faddeev-AGS approach was provided by the Lisbon group [17], which treats the Coulomb interaction with a screening and renormalization procedure. However, as the charge of the nucleus increases, technical difficulties arise in the screening procedure. To overcome this difficulty, the TORUS collaboration developed a new approach [44], where no screening of the Coulomb force is introduced. Therein, the Faddeev-AGS equations are cast in a Coulomb-distorted partial-wave representation instead of the traditional plane-wave basis. In order to bring this new theory laid out in [44] to fruition, well defined preparatory work needed to be successfully carried out.

Any momentum space Faddeev-AGS type calculation needs as input transition matrix elements in the different two-body subsystems. In the case of (d, p) reactions with nuclei, these are the transition matrix elements obtained from neutron-proton, neutron-nucleus, and proton-nucleus interactions. The use of the Coulomb basis as in [44] requires that those transition matrix elements are given in separable form. Thus, we needed to develop the different two-body interactions in separable form, we needed to develop the numerical representation of momentum-space partial-wave Coulomb functions, and the highly non-trivial (since oscillatory singular) numerical folding of the separable form factors with the Coulomb functions, before embarking on solving the three-body problem.

2.3.1 Separable Potentials for Nucleon Scattering off Closed-Shell Nuclei

Neutron Scattering off Closed-Shell Nuclei

Hlophe and Elster in collaboration with Nunes

Background and Purpose: One important ingredient for many applications of nuclear physics to astrophysics, nuclear energy, and national security applications are cross sections for reactions of neutrons with rare isotopes. Since direct measurements are often not feasible, indirect methods, e.g. (d,p) reactions, should be used. Those (d,p) reactions may be viewed as three-body reactions and described with Faddeev techniques. Faddeev equations in momentum space have a long tradition of utilizing separable interactions in order to arrive at sets of coupled integral equations in one variable. While there exist several separable representations for the nucleon-nucleon interaction, the optical potential between a neutron (proton) and a nucleus is not readily available in separable form. For this reason we first embarked in introducing a separable representation for complex phenomenological optical potentials of Woods-Saxon type.

Summary of results: We extended the well-known EST scheme [24] for creating separable representations of two-body transition matrix elements as well as potentials to the realm of complex potentials. Requiring that the separable transition matrix fulfill the reciprocity theorem, we identified a suitable rank-1 separable potential. In analogy to Ref. [24], we generalized this potential to arbitrary rank.

Our calculations were based on the Chapel Hill phenomenological optical potential CH89 [76]. Since the CH89 potential, as nearly all phenomenological optical potentials, is given in coordinate space using Woods-Saxon functions, we first give a semi-analytic Fourier transform of those Woods-Saxon functions in terms of a series expansion. In practice, it turns out that only two terms in the expansion are sufficient for achieving convergence. Note that our approach for deriving the momentum-space optical potential is general and can be applied to any optical potential of Woods-Saxon form. This momentum space CH89 potential is then used in the partial-wave LS integral equation to calculate half-shell t-matrices. These then serve as input to the the generalized scheme for creating separable representations for complex potentials.

We carried out studies of n+^{48}Ca, n+^{132}Sn and n+^{208}Pb, and are able to provide for all cases a systematic classification of support points for partial-wave groups, so that the partial-wave S-matrices are reproduced to at least 4 significant figures compared to the original momentum space solution of the LS equation. We find the low partial waves of the n+^{208}Pb system require a rank-5 separable potential to be well represented in the energy regime between 0 and 50 MeV center-of-mass energy. The support points obtained for this case are well suited to represent all partial waves of the n+^{208}Pb as well as all lighter systems described by the CH89 optical potential.

We found that the rank required for achieving a good representation decreases with increasing angular momentum of the partial wave considered. We developed recommendations for both the rank and the locations of support points to be used when describing medium-mass and heavy systems 0¿generated from the CH89 potential. Our recommendations group together partial waves. We also demonstrated that it is sufficient to determine support points including only the central part of the optical potential; when the spin-orbit interaction is added and the form factors are accordingly modified, the same support points can be expected to yield a good representation. This work was published in [31].

Proton Scattering off Closed-Shell Nuclei

Hlophe, Eremenko, and Elster in collaboration with Nunes and Upadhyay

Background and Purpose: To avoid a screening procedure Mukhamedzhanov derived a three-body theory for (d,p) reactions such that the Faddeev-AGS equations are cast in a momentum-space Coulomb-distorted partial-wave representation, instead of the plane-wave basis [44]. Thus all operators, specifically the interactions in the two-body subsystems must be evaluated in the Coulomb basis, which is a nontrivial task. The formulation also requires the interactions in the subsystems to be of separable form. Proton-proton (pp) scattering based on separable interactions was considered some time ago in [1] and [66, 65]. Therein the pp interaction was represented in terms of analytic functions, and the parameters in the two lowest partial waves were adjusted to describe the experimentally extracted pp phase shifts. While such an approach is viable in the pp system, it is not very practical when heavy nuclei are considered, since here many more partial waves are affected by the Coulomb force. Thus our approach for neutron-nucleus scattering must be adjusted to proton-nucleus scattering in order to create the input for (d,p) reaction calculations.

Summary of results: The derivations in the original EST work laid out in [24] set up the scattering problem in a complete plane-wave basis, whereas in this work we need to use a complete Coulomb basis. Consequently, when working in momentum space, we require a solution of the momentum space scattering equation in the Coulomb basis exists. We solve the momentum space Lippmann-Schwinger (LS) equation in the Coulomb basis, following the method introduced in Ref. [21] and successfully applied in proton-nucleus scattering calculations with microscopic optical potentials in Ref. [13].

For deriving a separable representation of the Coulomb-distorted proton-nucleus t-matrix element, we generalize the approach suggested by Ernst, Shakin, and Thaler (EST) [24], to the charged particle case. The basic idea behind the EST construction of a separable representation of a given potential is that the wave functions calculated with this potential and the corresponding separable potential agree at given fixed scattering energies E_i, the EST support points. The formal derivations of [24] use the plane wave basis, which is standard for scattering involving short-range potentials. However, the EST scheme does not depend on the basis and can equally well be carried out in the basis of Coulomb scattering wave functions. In order to generalize the EST approach to charged-particle scattering, one needs to be able to obtain the scattering wave functions or half-shell t-matrices from a given potential in the Coulomb basis.

To demonstrate the feasibility and accuracy of our method, we applied this momentum-space Coulomb EST scheme to proton elastic scattering from ^{12}C, ^{48}Ca, and ^{208}Pb. As example the unpolarized differential cross section for elastic scattering calculated in momentum space and compared with coordinate space values is given in Fig. 5. We found that the same EST support points employed to construct a separable representation of neutron-nucleus optical potentials can be used for the separable representation of the proton-nucleus potential [32]. We showed that the momentum-space S-matrix elements calculated with the separable representation of the Coulomb-distorted proton-nucleus potential as well as the cross sections for elastic scattering agree very well with the corresponding coordinate-space calculation. Since changing from a plane wave to a Coulomb basis preserves the time reversal invariance of the separable potential, the separable Coulomb-distorted proton-nucleus off-shell t-matrix also obeys reciprocity.

We also studied the effects of the short-range Coulomb potential on the proton-nucleus form factor. We found that, with the exception of the lowest partial waves the form factors already

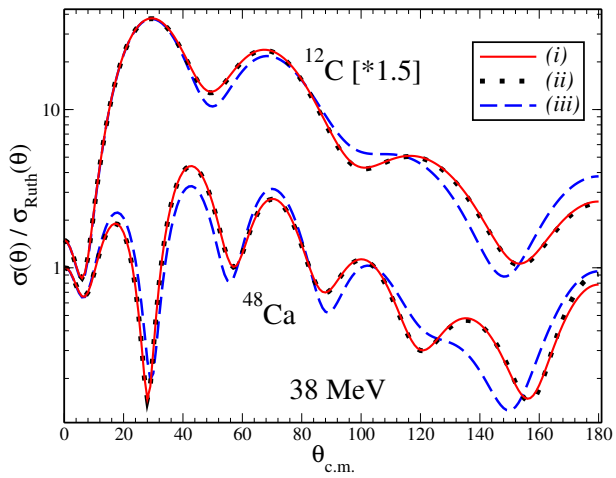

Figure 5: The unpolarized differential cross section for elastic scattering of protons from ^{12}C (upper) and ^{48}Ca (lower) divided by the Rutherford cross section as function of the c.m. angle calculated for a laboratory kinetic energy of 38 MeV. The ^{12}C cross section is scaled by a factor 1.5. The solid lines (i) depict the cross section calculated in momentum space based on the rank-4 separable representation of the CH89 [76] phenomenological optical potential, while the dotted lines (ii) represent the corresponding coordinate space calculations. The dashed lines (iii) show the results in which the short-ranged Coulomb potential is omitted.

vanish at 3.5 fm^{-1}. For the lowest partial waves the short range Coulomb force creates a very slow fall-off for the proton-nucleus form factor at high momenta. The effects of the short-range Coulomb potential quickly decrease as l increases.

In addition, this work demonstrates that when using Coulomb-distorted form factors in A(d,p)B Faddeev reaction calculations carried out in a Coulomb-distorted partial-wave basis, it is mandatory to evaluate neutron and proton-nucleus form factors separately. This work was published in Phys. Rev. C [32].

2.3.2 Partial Wave Coulomb Wave Functions in Momentum Space

Eremenko and Elster (OU) in collaboration with Upadhyay and Nunes (MSU)

Background and Purpose: The application of momentum space Faddeev techniques to nuclear reactions has been pioneered in Ref. [17], and successfully applied to (d,p) reactions for light nuclei [16]. However, when extending these calculations to heavier nuclei [48, 74], it becomes apparent that techniques employed for incorporating the Coulomb interaction in Faddeev-type calculations of reactions with light nuclei can not readily be extended to the heaviest nuclei. Therefore, a new method for treating (d,p) reactions with the exact inclusion of the Coulomb force as well as target excitation was formulated in Ref. [44]. This new approach does not rely on screening techniques but rather formulates the Faddeev equations directly in a Coulomb basis. In Ref. [44] generalized Faddeev equations with two charged particles were derived in the AGS form. In order for such an approach to be numerically practical, one needs to have exact expressions for the Coulomb wave function in momentum space as well as reliable techniques to calculate expectation values in this basis.

Summary and Results: The starting point are the Coulomb wave functions, which after a partial wave decomposition can be written as

$$\psi^C_{l,p}(q) \;=\; -\,\frac{2\pi\, e^{\eta\pi/2}}{pq}\;\lim_{\gamma\to+0}\;\frac{d}{d\gamma}\left\{\left[\frac{q^2-(p+i\gamma)^2}{2pq}\right]^{i\eta}\;(\zeta^2-1)^{-i\frac{\eta}{2}}\,Q_l^{i\eta}(\zeta)\right\}\;. \tag{3}$$

Here p is the magnitude of a fixed asymptotic momentum and $\zeta = (p^2+q^2)/2pq$. The Sommerfeld parameter is given as $\eta = Z_1 Z_2 e^2 \mu/p$ with $Z_1 Z_2 e^2$ being the total charge and μ the reduced mass of the two-body system under consideration. The spherical function $Q_l^{i\eta}(\zeta)$ in Eq. (3) can be expressed in terms of hyper-geometric functions ${}_2F_1$ as [29]

$$\begin{aligned} Q_l^{i\eta}(\zeta) \;=\; & \frac{e^{-\,\pi\eta}}{2}\Bigg\{\Gamma(i\eta)\,\left(\frac{\zeta+1}{\zeta-1}\right)^{\frac{i\eta}{2}}\;{}_2F_1\left(-l,l+1;\,1-i\eta;\,\frac{1-\zeta}{2}\right) \\ & +\Gamma(-\,i\eta)\,\frac{\Gamma(l+1+i\eta)}{\Gamma(l+1-i\eta)}\,\left(\frac{\zeta-1}{\zeta+1}\right)^{\frac{i\eta}{2}}\;{}_2F_1\left(-l,l+1;\,1+i\eta;\,\frac{1-\zeta}{2}\right)\Bigg\} \end{aligned} \tag{4}$$

under the condition that $|\arg(\zeta\pm 1)| < \pi$ and $|1-\zeta| < 2$, *i.e.*, $-1 < \zeta < 3$. However, care must be taken in its implementation, since there are specific limits of validity of the various expansions of hyper-geometric functions used in its derivation.

A considerable amount of analytical studies and comparisons with the *Mathematica* ® [58] software were carried out by Upadhyay and Nunes, with further details being given in the MSU report. Numerical implementation into robust a computational package and tests against the MSU results were carried out be Eremenko. This suite of codes evaluates the momentum space partial wave Coulomb wave functions for large range of Sommerfeld parameters ($10^{-1} \le \eta \le 10$) with a tested accuracy of about 10^{-6}.

The suite of codes together with a manuscript are published in *Computer Physics Communication* [23], and were already downloaded more than 50 times.

2.3.3 The Coulomb Problem in Momentum Space without Screening

Background and Purpose: Although the free Coulomb states constitute a basis as well defined as plane waves, the highly complicated nature of their momentum space representation makes it extremely difficult to obtain matrix elements with them. To our knowledge, our work represents the first attempt to obtain such matrix elements with relatively high values of charges. In order to have a chance of numerically realizing the proposed new formulation of Ref. [44] for (d,p) reaction in a Faddeev formulation, it is a mandatory that we carry out 'proof-of-principle' calculations by calculating Coulomb distorted form factors.

Tests with a Yamaguchi Formfactor

Upadhyay and Nunes (MSU) in collaboration with Eremenko, Hlophe and Elster (OU)

Summary and Results: Given the challenge of calculating not only the partial wave Coulomb wave functions $\psi^C_{l,q}(p)$, but also handling their oscillatory singularity when $p = q$ when evaluating

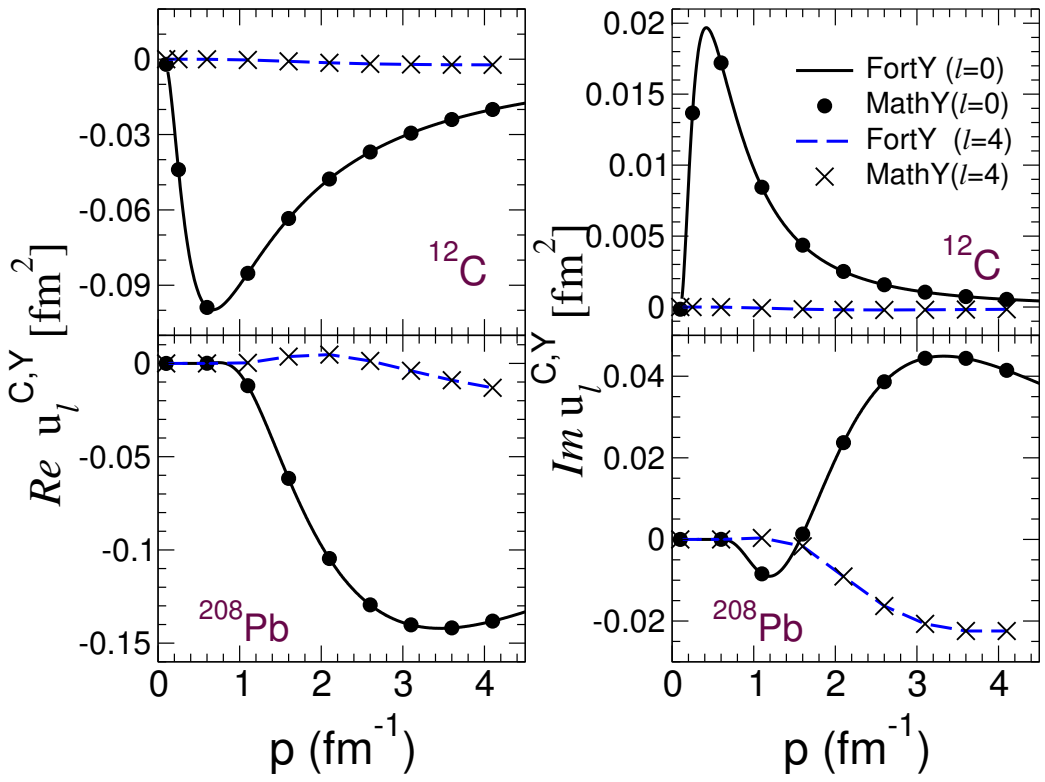

Figure 6: (Color online) The partial wave Coulomb formfactors $u_l^C(p)$ obtained with a Yamaguchi interaction as a function of the external momentum p for selected angular momenta l. Comparison between our numerical evaluation (solid lines) and the *Mathematica*® [58] results (symbols).

integrals of the type

$$u_l^C(p) = \int_0^\infty \frac{dq\ q^2}{2\pi^2}\ u_l(q)\ (\psi_{l,p}^C)^\star(q), \tag{5}$$

where $u_l(q)$ is the nuclear form factor, we first used Yamaguchi functions as form factors. Using a Yamaguchi formfactor as a test case has the advantage that calculations can be performed not only numerically but also semi-analytically, in our case using the *Mathematica* ® [58] software. The Coulomb distorted formfactors, $u_l^{C,Y}(p)$ calculated as integral over the Coulomb wave function given in Eq.(5) and the Yamaguchi formfactor from [44] are depicted in Fig. 6, where our numerical results (labeled FortY) are compared with those from *Mathematica* ® [58] (labeled MathY). The top panels concern protons on ^{12}C and the bottom panels refer to protons on ^{208}Pb. On the right (left) we show the real (imaginary) parts of $u_l^{C,Y}(p)$. Both $l = 0$ and $l = 4$ are shown.

As shown in Fig. 6, the Coulomb distorted Yamaguchi formfactors obtained with our numerical implementation agree perfectly well with the results obtained with *Mathematica*®. To achieve this level of agreement in the form factors, we first compared the accuracy of our numerical implementation of the Coulomb wave functions with the corresponding results provided by *Mathematica*®. The agreement found was of the order of 10 significant figures. Next, we compared the accuracy of the integration given by Eq. (5) and found that our numerical calculation agreed with the corresponding *Mathematica*® calculation to about 6 significant figures. This demonstrates that our numerical implementation of the Coulomb wave functions, integration and regularization tech-

niques, provides a reliable method for calculating form factors involving Coulomb wave functions in momentum space.

In order to explore the importance of the region around the singularity, we have performed additional calculations where we removed a region $p \in [q-\Delta, q+\Delta]$ around the pole $p = q$ from the integral of Eq. (5). In Fig. 7 we show the absolute value of the relative difference between the results $u_l^{C,Y}(p,\Delta)$, obtained removing the pole region, and the full integral $u_l^{C,Y}(p)$, i.e. the quantity

$$\mathbf{D}(\Delta) = \frac{|u_l^{C,Y}(p) - u_l^{C,Y}(p,\Delta)|}{|u_l^{C,Y}(p)|} \tag{6}$$

for fixed values of q. We choose $p = 0.6$ fm^{-1} ($E_{c.m.} = 8.1$ MeV) for ^{12}C and $p = 1.1$ fm^{-1} ($E_{c.m.} = 7.5$ MeV) for ^{208}Pb, as examples. For each of these values of p the nuclear formfactor is far from any node. In Fig. 7 the calculations of the above defined quantity $\mathbf{D}(\Delta)$ are shown as function of Δ for p+^{12}C (top), and for p+^{208}Pb (bottom), for the $l = 0$ (dot-dashed lines) and $l = 4$ (dashed lines). In case of ^{12}C we find that the relative difference is always around 10% or larger, independent of the Δ used and independent of the partial wave. Expectedly, the situation for ^{208}Pb is worse, discrepancies are about two orders of magnitude for $l = 0$ and one order of magnitude for $l = 4$. The demonstration given in Fig. 7 emphasizes the importance of the pole region.

After finalizing the tests with the Yamaguchi, the codes developed at MSU were ported to OU, for implementation of the realistic interactions using the separable nuclear form factors based on optical potentials (see section 2.3.1) [31, 32]. All details on the implementation of Eq.(5) and the physical cases studied were published in [75]. This work enabled us to understand the general features we obtain for the Coulomb distorted form factors.

Implementation with realistic interactions

Upadhyay and Nunes (MSU) in collaboration with Eremenko, Hlophe and Elster (OU)

Summary and Results: After successfully establishing that we correctly implemented the regularization scheme proposed by Gel'fand and Shilov [27], we used the Woods-Saxon type form factors derived in Ref. [31], after adjusting them to p+nucleus scattering.

In Fig. 8 we show in the left panels non-distorted form factors from the separable optical potentials for n+^{12}C, n+^{48}Ca, and n+^{208}Pb. The right panels show the corresponding Coulomb distorted form factors. At zero momentum the nuclear form factors are finite for $l = 0$ while going to zero as p^l for all higher angular momenta as dictated by the partial wave decomposition of the two-body t-matrix they are derived from. In contrast, the Coulomb distorted form factors is also zero for $l = 0$ at $p = 0$. This is associated with the existence of a repulsive barrier at the origin. Comparing the left and right panels of Fig 8 also shows that the Coulomb interaction generally pushes the structure of the form factors from lower momenta to higher momenta. In addition we observe that the heavier the nucleus, the more structure the corresponding form factors exhibit. However, it is interesting to note, that for all nuclei under consideration the form factor goes to zero already at 3 to 4 fm^{-1}, which is a property of the underlying Woods-Saxon ansatz.

In order to carefully study the role of the pole region in the integral of Eq. (5), we perform the integration, but leave out a region of momenta around the pole $p \in [q-\Delta, q+\Delta]$ when computing the integral. In Fig. 9 we compare the complete calculation of the real part of the $l = 0$ Coulomb

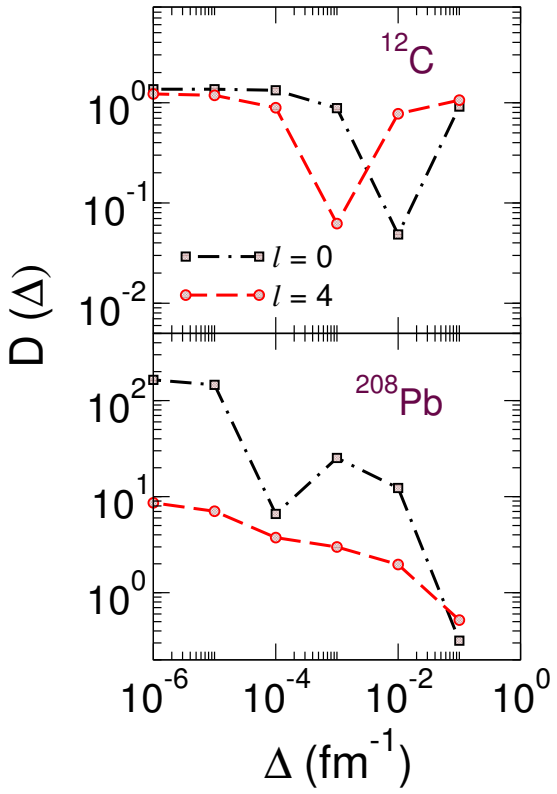

Figure 7: (Color online) The relative difference $\mathbf{D}(\Delta)$ of the exactly calculated integral of Eq. (5) and the integral without including the region $\pm\Delta$ around the pole as a function of Δ for p+^{12}C at $p = 0.6$ fm^{-1} (top) and p+^{208}Pb at $p = 1.1$ fm^{-1} (bottom). Shown are l=0 (dot-dashed) and l=4 (dashed) partial waves.

distorted form factor, $u_0^C(p)$, for ^{12}C with calculations of the same integral in which a region Δ around the pole at p was "blended out", i.e. neglected. The complete calculation is the same as shown in Fig. 8. We find that for large Δ (say $\Delta = 0.1$ fm^{-1}) the form factor has little resemblance with the exact one. As Δ becomes smaller, at least in the higher momentum region one can see a continuous build-up towards the exact result. In Fig. 10 we show the identical calculations for the real part of the $l = 0$ form factor for the ^{208}Pb form factor. Here we find that although for all values of Δ considered the form factor computed without the pole region follows the shape of the full form factor, it has quite different values.

To obtain some qualitative insight into this behavior, one has to have the functional form of the Coulomb wave function, $\psi_{l,p}^C(p')$, in mind and consider the dependence on the Sommerfeld parameter η. The smaller η, the more narrowly peaked around the pole p the Coulomb wave function becomes. In case of the ^{208}Pb form factor calculation shown in Fig. 10, η is large and $\psi_{l,p}^C(p')$ has a relatively broad distribution around the pole at p. Consequently, in the integration a relatively large momentum interval of the nuclear form factor $u_l(p')$ contributes. In the case of ^{12}C the Sommerfeld parameter η is already an order of magnitude smaller, and decreases further as function of p, making the momentum distribution of the Coulomb wave function much narrower. In the small p region of Fig. 9 only a relatively small momentum region of the smooth nuclear form factor contributes to the integral. For larger p the value of η becomes smaller and the momentum

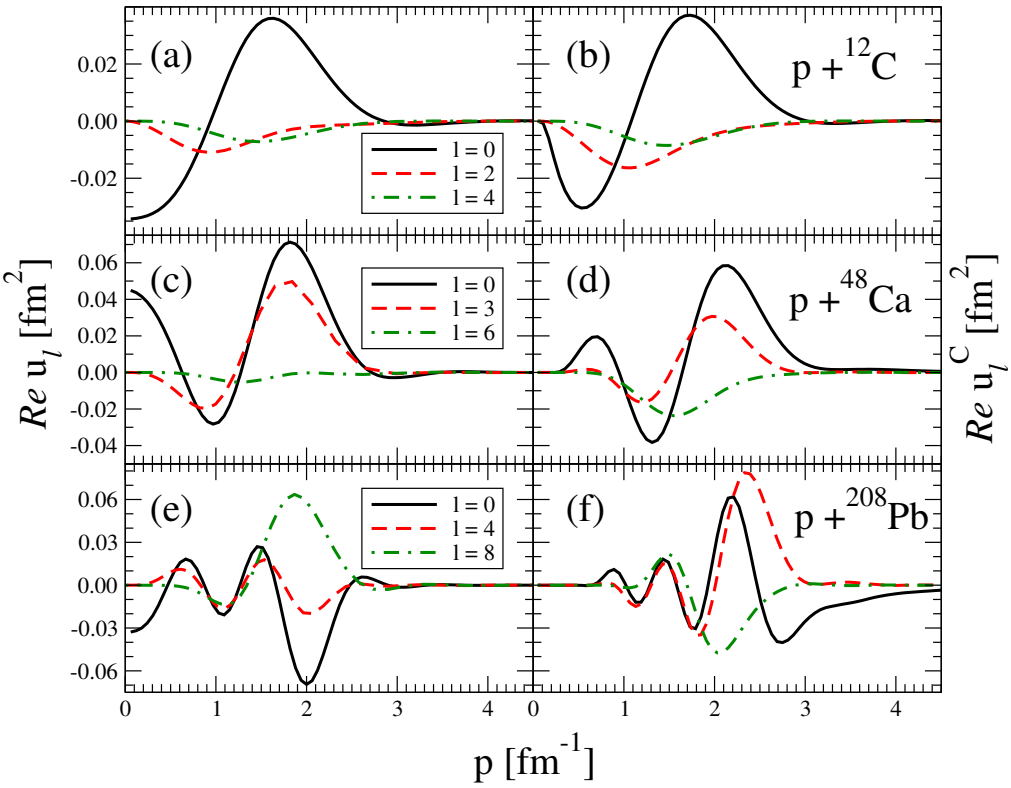

Figure 8: The real parts of the partial wave nuclear form factors $u_l(p)$ (left panels) and the Coulomb distorted nuclear form factors $u_l^C(p)$ (right panels) as function of the the external momentum p for selected angular momenta l: (a) $\Re e\ u_l(p)$ for n+^{12}C; (b) $\Re e\ u_l^C(p)$ for p+^{12}C; (c) $\Re e\ u_l(p)$ for n+^{48}Ca; (d) $\Re e\ u_l^C(p)$ for p+^{48}Ca. (c) $\Re e\ u_l(p)$ for n+^{208}Pb; (d) $\Re e\ u_l^C(p)$ for p+^{208}Pb. The form factors for ^{12}C correspond to the fixed support point E_{cm} = 30 MeV, that for ^{48}Ca is at a fixed support point E_{cm} = 36 MeV, while the nuclear form factors for ^{208}Pb are at a fixed support point E_{cm} = 36 MeV for $l = 0, 4$, and E_{cm} = 39 MeV for $l = 8$.

distribution of the Coulomb wave function even narrower, so that only a very restricted momentum region of the nuclear form factor contributes, leading to the appearance of an almost build-up to the final answer. The Coulomb wave functions contain as one of the leading terms the factor $\exp(-\pi\eta)$, see Eq. (5), thus for large values of η, the contributions in the integrand are smaller. This explains that the variations of the integral for small momenta p are much smaller for ^{208}Pb than for ^{12}C. For example, the value $\eta \sim 1.6$ occurs for ^{12}C at $p \simeq 0.12$ fm^{-1}, while for ^{208}Pb at $p \simeq 1.8$ fm^{-1}. For those momenta both figures show a strong variation of the integral as function of Δ. Once the momenta p become larger, η quickly becomes smaller. In summary, both of these demonstrations show that it is of uttermost importance to carefully treat the pole region in the integral of Eq. (5), since major contributions to this integral come from the region around the pole.

We further implemented Coulomb distorted form factors into the EST formulation for separable optical potentials. In Ref. [12] a rank-1 separable potential was constructed including Coulomb distortions. We implemented a similar approach within the EST scheme. However, since using the sum of Coulomb distorted form factors to construct a p+nucleus optical potential is in general **not** equal to approximating a local Coulomb distorted nuclear potential by a sum of EST form

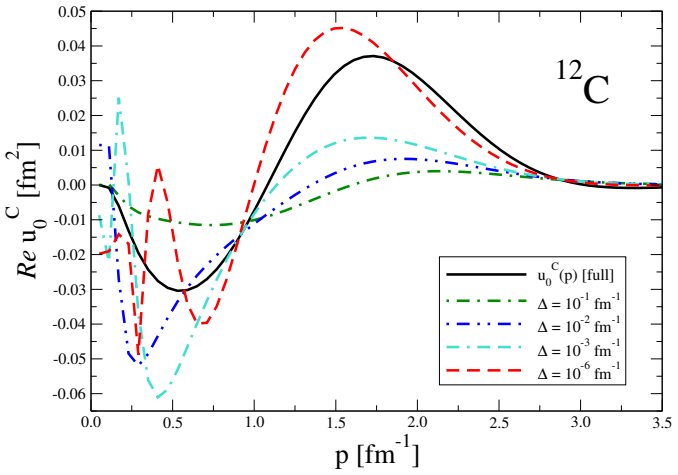

Figure 9: The real part of the $l = 0$ the Coulomb distorted nuclear form factors $u_0^C(p)$ as function of the the external momentum p for ^{12}C at the fixed support point E_{cm} = 30 MeV. The solid (black) line shows the full results, while for all other curves an interval of the size Δ has been cut out left and right of the pole p while performing the integration.

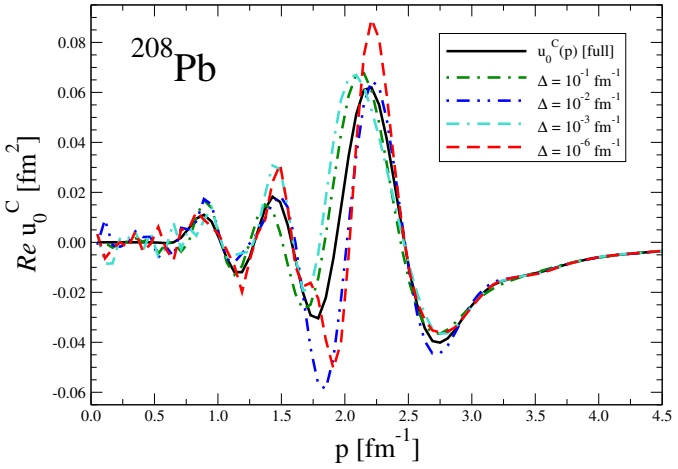

Figure 10: The real part of the $l = 0$ the Coulomb distorted nuclear form factors $u_0^C(p)$ as function of the the external momentum p for ^{208}Pb at the fixed support point E_{cm} = 36 MeV. The solid (black) line shows the full results, while for all other curves an interval of the size Δ has been cut out left and right of the pole p while performing the integration.

factors, this procedure is not a substitute for dealing with the pinch-singularity which occurs when deriving the expressions for a nuclear potential in Coulomb basis [21]. These results are published in Ref. [75].

2.3.4 Further work on Faddeev-AGS equations

Eremenko, and Elster in collaboration with Nunes

Coulomb modified Faddeev-AGS Equations For developing a scheme in which (d,p) reactions can be calculated for heavy nuclei, Mukhamedzhanov [44] derives a three-body formulation which does not include screening of the Coulomb force. Therein, the Faddeev-AGS equations are cast in the Coulomb-distorted partial-wave representation instead of the plane-wave basis. Most of our effort has concentrated in practical implementations of the basis and calculating matrix elements of two-body quantities, i.e. form factors, in this basis.

There is however one more issue to deal with, which is ignored in Ref. [44]. For all practical applications the Faddeev-AGS equations are written in Jacobi coordinates, which allows to cleanly separate the center-of-mass momentum and solve the equations in relative coordinates [28]. If two of the three particles are charged, this leads to the well known problem that the repulsive Coulomb potential is in the 'wrong' coordinates in two of the coupled Faddeev-AGS equations [7, 18], since the corresponding Jacobi coordinate of the charged spectator points to the center-of-mass of the pair. In Ref. [44] this issue was not addressed. However, since we are working with Coulomb Green's functions given in Jacobi coordinates, we absolutely must address it and revise the equations of Ref. [44]. Postdoc Vasily Eremenko is currently in the process of reformulating the equations so that they match the formulation we already started to use.

Faddeev-AGS equations in Partial Waves As a next step to the numerical realization of the momentum space Faddeev-AGS equations, postdoc Vasily Eremenko derived the general formulation for the iso-spin and spin-angular momentum couplings between for the partial wave equations. Since we work with three distinguishable particles (neutron, proton, and nucleus), we have three coupled Faddeev equations, which need to be represented in a partial wave basis. We work in relative Jacobi coordinates, and have the three different choices of pair and spectator particle, which are all equivalent. One specific basis is picked to carry out the calculation and all other parts of the equations need to be expressed in this basis, leading to a set of iso-spin and spin-angular momentum re-couplings. In deriving those we follow the scheme of Balian-Brezin [6, 35], which takes advantage of the rotational symmetry for specific axes in the explicit evaluation.

2.4 Capture Reactions

Arbanas, Thompson and Escher in collaboration with Shi-Sheng Zhang and the ORNL Experimental Nuclear Astrophysics Group

We have extended methods of computing direct and semidirect capture on spherical and non-spherical nuclei in the coupled-channels framework implemented in the Fresco code [70]. A significant component of this effort was performed to help motivate and support various experimental measurements at HRIBF and at TRIUMF in order to provide theoretical estimates of capture cross sections.

2.4.1 Direct-semidirect capture via Giant-Dipole and Isobar-Analogue Resonances

The position and width of isobaric analogue resonances in nucleon-nucleus scattering are accurate and detailed indicators of the positions of resonances and bound states with good single-particle characters [8]. Since determining the positions of shells and shell gaps has often been the objective of experiments with unstable isotopes, measuring isobaric analogue resonances (IAR) should be

modeled as well as possible by theorists in relation to proposed experiments. These IAR have the great virtue that *neutron* bound states, both occupied and unoccupied, can be determined in experiments that react *protons* on nuclei. Proton targets can be made with hydrogen. The best information about levels is determined by (p,p$'\gamma$) coincidence experiments [56]. The displacement energies of IAR also depend critically on neutron-proton density differences, so can be used to probe those densities in the surface.

We therefore implemented within our coupled-channels code FRESCO the main Lane coupling term [2]: the interaction that couples an incident proton to a neutron at a lower energy, such as a sub-threshold energy near an unoccupied single-particle state. We see doorway resonances when the neutron energy is near a bound state. At the same time, a target neutron must have changed to a proton, so it must have been in an occupied neutron state with quantum numbers such that a proton with those parameters is not Pauli blocked. We therefore extended the Lane coupled-channels formalism to follow the non-orthogonality of this neutron channel with that configuration of an inelastic outgoing proton, and the target being left in a particle-hole excited state. We described the method and presented computed (p,p$'\gamma$) in [68]: we find that the energies of IARs correspond almost exactly with the energies of single-particle neutron states in ^{208}Pb and that our computation reproduces essential features of (p,p$'\gamma$) cross section.

We have described our coupled-channel method of direct-semidirect capture (DSD) via giant-dipole resonances (GDR) in [69] and find a general agreement with conventional GDR models and data for ^{208}Pb(n,γ) capture. Although the effect of GDR at low energies of interest to nuclear astrophysics is small on stable nuclei, a low-energy electric-dipole strength (a.k.a. pygmy resonance) seen in neutron rich nuclei was a motivating factor for revisiting DSD capture in this collaboration.

2.4.2 Computation of direct-semidirect capture ^{130}Sn(n,γ)

Capture cross sections on and near doubly closed shell nuclei like ^{132}Sn are needed to improve the accuracy of astrophysical nucleosynthesis models. This motivated our collaborator R. Kozub to measure of ^{130}Sn(d,p)^{131}Sn in inverse kinematics, from which single-particle energies and spectroscopic factors in ^{131}Sn were computed. These single-particle level parameters were then used to compute direct-semidirect (DSD) capture process ^{130}Sn(n,γ)^{131}Sn using FRESCO and an older DSD code CUPIDO. For neutron energies 5-20 MeV we find the semidirect capture via giant-dipole resonance to be dominant over direct capture, but for neutron energies below 1 MeV, of interest to astrophysical nucleosynthesis models, we find semidirect to be less than 5% of the direct capture. Likewise, measurements of (d,p) [14] were performed on ^{124,126,128}Sn isotopes in inverse kinematics and corresponding direct capture cross sections were computed [B. Manning *et al.*, in preparation].

Our computed direct-semidirect (DSD) capture ^{130}Sn(n, γ) are shown in Fig. 11 (published in [38]). Thus the uncertainty of the computed direct capture (by various models shown in this figure) was reduced by orders of magnitude. Besides the DSD capture, we attempted to address the applicability of the compound nuclear (i.e. statistical) capture computations, by using various statistical models implemented in TALYS, since the input to the nucleosynthesis models requires a total capture cross section that is a combination of the DSD and compound captures. TALYS models of statistical capture cross section indicate it is significantly larger than direct capture. We have suggested that validity of these calculations could be estimated by measuring deuteron stripping reaction (d,pn) into neutron continuum just above the neutron separation energy, as this

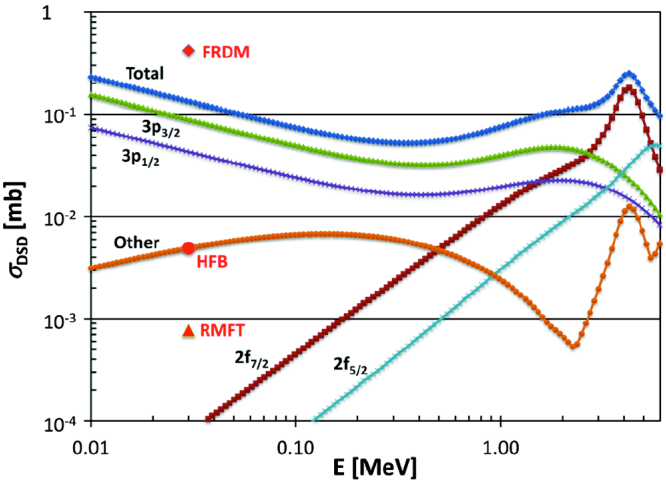

Figure 11: Computation of direct-semidirect neutron capture cross section for the ^{130}Sn(n, γ) reaction reported in [38]. Shown for comparison (single points) are the calculations for 30 keV neutrons using the finite range droplet (FRDM), the Hartree- Fock-Bogoliubov (HFB), and relativistic mean field theory (RMFT) models. Of these, only the FRDM predicted both the $3p_{3/2}$ and $3p_{1/2}$ single-neutron states to be bound.

cross section would be amplified by compound nuclear resonant states, the same states that would significantly enhance neutron capture cross section. Based on these suggestions, experiments to measure (d,p) and (d,pn) cross sections on unstable isotopes in inverse kinematics are currently proposed by our collaborator Barry Davids and his group at TRIUMF, in part to advance theories of statistical nuclear reactions beyond the conventional Hauser-Feshbach formula (see Sec. 2.5 for additional information).

2.4.3 Consistency of capture and stripping models for non-spherical nuclei

Models of direct neutron capture of neutrons have accounted for the effects of non-spherical nuclei either in the incoming wave functions (via non-spherical optical model potentials), *or* in the final bound states (via non-spherical real potential wells), but not in both. Since it is known that spherical optical potentials do not give a good reproduction of low energy neutron-scattering observables of deformed nuclei, we have performed calculations in which the initial and final states are both treated in a self-consistent, non-spherical-nucleus picture. We have done this in the coupled-channels model of nuclear reactions implemented in the FRESCO code [70] by using the same deformation-length for the couplings to the 2^+, 4^+, and 3^- collective states in the incoming *and* the final state configurations, shown in Fig. 12. We compute direct capture using the new and the conventional method for even-mass calcium isotopes ^{40,42,44,46,48}Ca and find that the new method yields substantially smaller direct capture and deuteron stripping cross sections than the conventional method in between the two closed shells with a minimum at ^{44}Ca. (Furthermore, we find that the deformation in the final state has a larger effect on the cross section.)

Motivated by these findings, we have computed (d, p) cross section on non-spherical nuclei by introducing coupling to the same set of collective states, in analogy to the (n, γ) computations already performed, in order to examine the connection between (d, p) and (n, γ) cross sections for non-spherical nuclei. The results shown in Fig. 13 suggest that spectroscopic factors for non-spherical nuclei extracted from (d, p) reaction ought to be re-fitted in a consistent treatment of

deformation in these two reactions.

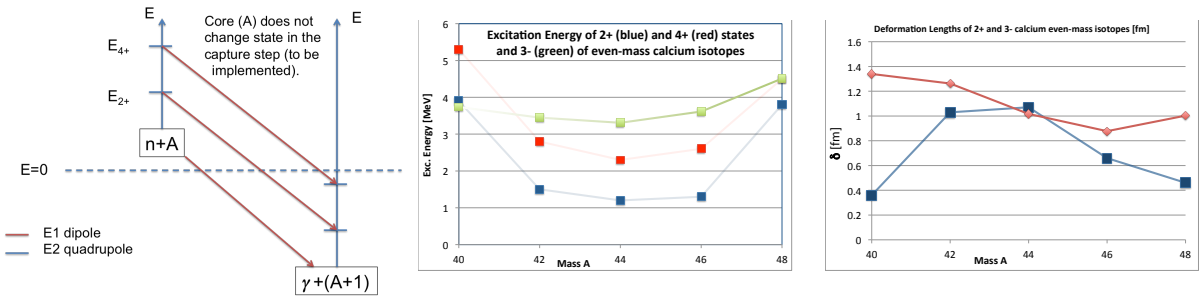

Figure 12: A schematic diagram showing couplings between the ground state, 2^+, and 4^+ quadrupole states in our coupled-channel model of neutron capture and deuteron stripping (a), and the energies (b) and deformation lengths (c) of those states for ^{40,42,44,46,48}Ca isotopes used in our FRESCO computations.

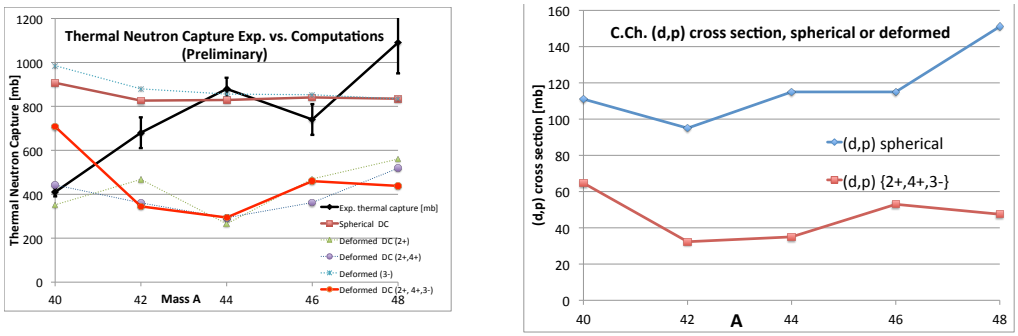

Figure 13: Fresco computations of thermal neutron capture (a) and deuteron stripping (b) with coupling to 2^+, 4^+, and 3^- collective states in our coupled-channel model on ^{40,42,44,46,48}Ca isotopes. These results suggest that re-fitting of spectroscopic factors to the (d,p) data would make (n,γ) computations more consistent with the capture data. The decrease observed for deformed (d,p) calculations suggest that an off-setting increase in spectroscopic factors would increase the computed capture cross section for a better agreement with the data.

2.4.4 Direct neutron capture with covariant density functional theory inputs

In a long-term collaboration with Shi-Sheng Zhang we have explored direct capture on several doubly closed shell nuclei for which direct capture is expected to be the largest contribution to the total capture [79].

Models of direct neutron capture are of vital importance for simulations of nucleosynthesis in supernovae, merging neutron stars, and other astrophysical environments. We calculated direct capture cross sections using nuclear structure information obtained from a covariant density functional theory as input for the FRESCO coupled reaction channels code in a spherical approximation (*i.e.* without coupling to collective states described earlier in this subsection.) We investigated the impact of pairing, spectroscopic factors, and optical potentials on our results to determine a robust method to calculate cross sections of direct neutron capture on exotic nuclei. Our predictions

agree reasonably well with experimental cross section data for the closed shell nuclei ^{16}O and ^{48}Ca, and for the exotic nucleus ^{36}S. We then used this approach to calculate the direct neutron capture cross section on the doubly magic unstable nucleus ^{132}Sn which is of interest for the astrophysical r-process (see Sec. 2.4.2).

2.5 Other work

Nunes and others at MSU

Luke Titus, an MSU PhD student, in collaboration with Nunes, have been investigating nucleon-nucleus non-local potentials. Titus has developed a code to solve the scattering problem with non-local interactions (manuscript submitted) and is developing the formalism to be able to include non-local interaction in the calculation of transfer reactions within the adiabatic wave approximation. Luke Titus is funded partly by NNSA and partly by NSF.

Nunes was involved in the interpretation of the GRETINA data taken at NSCL to study the reaction ^{56}Ni(d,n)^{57}Cu (manuscript in preparation).

Nunes collaborated with Fred Sarazin from Colorado (and his former student Duane Smalley) on the analysis of TRIUMF data for the reaction ^{12}C(^{6}He,^{4}He)^{14}C, as well as the writing of the paper [67].

Nunes collaborated with Kate Jones from University of Tennessee (and her former student Kyle Schmitt) on the analysis of the ORNL data on ^{10}Be(d,p)^{11}Be, as well as the writing of the paper [63].

Elster and others at OU

In the context of microscopical optical potentials, Elster, Weppner and Ph.D. student A. Orazbayev finished their work on open shell effects in a microscopic optical potential for elastic scattering ^{6}He and ^{8}He. In this work elastic scattering observables (differential cross section and analyzing power) are calculated for the reaction ^{6}He(p,p)^{6}He at projectile energies starting at 71 MeV/nucleon. The optical potential needed to describe the reaction is based on a microscopic Watson first-order folding potential, which explicitly takes into account that the two neutrons outside the ^{4}He-core occupy an open p-shell. The folding of the single-particle harmonic oscillator density matrix with the nucleon-nucleon t-matrix leads for this case to new terms not present in traditional folding optical potentials for closed shell nuclei. The findings of this work are published in [52].

Nuclei in which the neutron halos involve neutrons in a p-wave relative to the core (e.g. ^{6}He, ^{11}Li) relate to important issues of whether the mechanism of binding in Borromean systems with subsystems involving resonant p-wave interactions is universal. For example, we can ask which features of these systems (e.g. neutron separation energies, radii, E1 dissociation cross sections) are correlated with the energy of the p-wave neutron-core resonance. In order to address this question the Faddeev equations for a three-body system with two (zero-range) resonant p-wave interactions were solved. This was the last part of Chen Ji's Ph.D. work, and was done in collaboration with Phillips and Elster. These results were published in [36].

Elster and collaborator Polyzou (U. Iowa) developed a relativistic formulation of reaction theory for nuclei with a dynamics given by a unitary representation of the Poincaré group [55]. Relativistic dynamics is introduced by starting from a relativistic theory of free particles to which

rotationally invariant interactions are added to the invariant mass operator. Poincaré invariance is realized by requiring that simultaneous eigenstates of the mass and spin transform as irreducible representations of the Poincaré group. As explicit example, a Poincaré invariant formulation of a (d,p) reaction as a three-body problem is given.

Escher, in collaboration with experimentalists from U Richmond and LLNL

The interplay of direct and compound mechanisms in one-nucleon transfer reactions has been of interest to the TORUS collaboration. J. Escher has been working with experimental colleagues from the University of Richmond and from LLNL to study one-nucleon (p,d) transfer reactions that produce intermediate nuclei at excitation energies near and above the particle thresholds. Measurements, carried out Lawrence Berkeley Laboratory and at the Texas A&M Cyclotron Laboratory, for (p,d) reactions on gadolinium, yttrium, and zirconium nuclei, have generated new insights into shell structure and the interplay of direct and compound-nuclear processes. This work resulted in 7 regular publications [34, 59, 60, 62, 33, 61, 53] and two conference proceedings [57, 54].

Escher, in collaboration with theorists from Sao Paulo, Brazil

In collaboration with Mahir Hussein (Universidade de São Paulo, Brazil) and Brett Carlson (São José dos Campos, SP, Brazil), J. Escher has been revisiting the present status of theoretical descriptions of compound-nuclear reactions. An invited paper for a special volume on Open Problems in Nuclear Reaction Theory was published in Journal of Physics G [11].

Arbanas and others at ORNL

Within a fruitful collaboration between TORUS and the ORNL's Experimental Nuclear Astrophysics Group we have recently started working with Brett Manning (a graduate student for Jolie Cizewski at Rutgers University), on computation of neutron capture cross sections on even tin isotopes ^{124,126,128}Sn. Brett has extracted single-particle spectroscopic factors from (d,p) measurements he performed at the ORNL over the previous 2.5 years. This work is the continuation of similar work we have already performed for ^{130,132}Sn and other nuclides.

Arbanas has initiated a complementary collaboration with Marek Płoszajczak and Nicolas Michel of GANIL, France, to compute neutron capture cross sections in the framework of the Gamow Shell Model for isotopes near ^{132}Sn(n,γ) and other doubly-closed shell nuclei. This work will investigate contributions of many particle-hole components components of resonant and bound states to the capture cross section. This work will be funded by the ORNL's Small SEED Money Fund, while a FUSTIPEN grant paid for a two-week exploratory visit by Arbanas to GANIL, May 31 - June 12, 2015.

Arbanas is collaborating with Barry Davids of TRIUMF, Canada, on various proposals to use state-of-the-art EMMA spectrometer and the SHARC detector array for inverse kinematics measurements of deuteron stripping reactions into bound states or continuum, for examples measurements of ^{88}Rb(d,p) and similar reactions have been and will be proposed for beam time at the TRIUMF because very little is known about ^{88}Rb, including the spins and parities of most of its states. The nucleus ^{88}Rb has just one neutron beyond the N = 50 closed neutron shell and is therefore an excellent case for inferring the (n,γ) cross section from (d,p) measurement. The neutron-capture cross section of ^{88}Rb will serve as an important input for "cold" r-process calculations.

Arbanas and Thompson

During 2013 we had a lengthy correspondence with Rituparna Kanungo (Saint Mary's University) about the ^{63}Ni(d,p) measurement planned at TRIUMF, that was to complement the recent

nTOF's measurement of ^{63}Ni(n,γ). We observed that that computations of direct-capture in this mass range may be unreliable, and that narrow compound p-wave resonances in the capture cross section are a significant contributor to the stellar Maxwellian-averaged cross sections. It was concluded that a suggested measurement of deuteron stripping into bound states alone, for the sake of extracting spectroscopic factors and computing direct capture cross section, would likely yield a small fraction of the total capture cross section on this isotope.

3 Project Management

Coordination

- The coordinating P.I. coordinated the different sub-projects, to ensure the cohesion of the overall project.
- Monthly conference calls ensured that practical information was exchanged, and that research projects, visitors and collaborations were properly coordinated.
- Additional conference calls were set up as needed, and our website (see below) was used to deposit internal documents for discussion.
- Collaborative visits and small-group conference calls were held on a regular basis to allow for detailed discussions of physics issues.

Website

We have developed a website at http://www.reactiontheory.org that is hosted at MSU. For the public, this site contains general information about our collaboration, our research papers and talks, the workshops and conferences we attend, and lists of relevant experiments.

For ourselves (protected by a password), we had information about our budget, our plans and deliverables, minutes from our meetings and conference calls, and also a place to deposit internal documents for access by the collaboration.

4 Research Staff

4.1 Postdoctoral Staff

TORUS Postdoctoral researcher Dr Neelam Upadhyay

Dr Upadhay's first project benchmarked the Continuum Discretized Coupled Channel (CDCC) method against the current implementation of the Faddeev AGS method, leading to the published comparison [74].

Neelam's second project focused on the numerical implementation of the momentum-space Coulomb distorted wave representation. The first part of this was the implementation of the partial wave Coulomb wave function in momentum space was performed and published [75]. Next, the

Coulomb distorted form factors discussed in Section 2.3.2 were implemented both in Fortran90 and Mathematica for verifying the results of [32].

Dr. Upadhyay went to postdoc position at Louisiana State University in August 2013 to work with Jerry Drayer and his group, and subsequently returned to India.

TORUS Postdoctoral researcher Dr Vasily Eremenko

Dr. Eremenko started as postdoctoral researcher at Ohio University May 1, 2013, after having spent about half year at Texas A&M University, working with A. Mukhamedzhanov on the TORUS (d,p) reaction effort.

He led the work for the publication for *Computer Physics Communication* [23], since we need the Coulomb wave functions in momentum space. In addition, his careful work has made it possible to deliver the proof-of-principle calculation of Coulomb distorted form-factors for nuclei from ^{12}C to ^{208}Pb, using at Gelfand-Shilov regularization of the oscillating singularity in momentum integrals over a formfactor and a Coulomb wave function [75].

For his second year at Ohio University, Dr. Eremenko was funded by the OU nuclear theory group grant. During this time he developed the partial wave representation of the Faddeev-AGS equations as needed for a (d,p) reaction calculation, and then focused on the derivation of Coulomb modified Faddeev-AGS equations based on the theory [44] of Akram Mukhamedzhanov in collaboration with him.

Dr. Eremenko will move on to a staff position at the Skobeltsyn Institute of Nuclear Physics at Moscow State University in September 2015.

4.2 Students

Ohio University doctoral student Mr Linda Hlophe

The TORUS grant supported Ohio University graduate student Linda Hlophe during the Spring quarter 2012, and the Spring semester 2013. After this he has been supported by the DOE contract No. DE-FG02-93ER40756 with Ohio University.

Linda Hlophe developed the separable representation of n+nucleus optical potentials for ^{12}C, ^{48}Ca, ^{132}Sn, and ^{208}Pb. This work appeared in Physical Review C [31]. Following his n+nucleus work, Linda concentrated on the separable optical potentials for p+nucleus, i.e. providing the nuclear formfactor which were used by Dr. Eremenko to calculate Coulomb distorted formfactors in [23]. He reworked his codes in more general terms, so that they can take any EST formfactor and calculate the corresponding separable optical potential. By this, the modifications, which have to occur for p+nucleus scattering are automatically included. Linda further developed the code to compute S-matrix elements and p+nucleus phase shifts, so that the partial wave s-matrix elements (and phase shifts) calculated with the separable potential computed with Coulomb distorted form factors can be compared to exact calculations made by FRESCO. This work was more involved than initially anticipated, but was published as [32] and will be part of his Ph.D. thesis.

Furthermore, Linda Hlophe decided to stay with the TORUS collaborators for his remaining thesis work. He will develop the separable coupling potentials needed to add the transfer to resonances or bound states with a small binding energy, needed in the development of a Faddeev based

(d,p) reaction code.

Linda Hlophe will graduate in Summer 2016.

4.3 Visitors supported by the grant

The grant contributed to the sabbatical support of Prof. Stephen Weppner, who spent the academic year 2010-11 at Ohio University. After that, Prof. Weppner visited OU for about 2 weeks each in 2012, 2013, and 2014.
The grant supported the visits of Dr Antonio Fonseca in 2010, of Dr Seth Waldeck in 2011, of Drs Ron Johnson and R. Lazouskas in 2013, and of Dr Arnoldas Deltuva in 2012 and 2015.

4.4 Travel supported by the grant

The grant supported the travel of the PI, postdoc Eremenko, and graduate student Linda Hlophe to conferences in which TORUS research was presented. Those were the DNP meetings during the grant period, the International Few-Body Conferences in Fukuoka (2012) and Chicago (2015), the European Few-Body Conference in Kracow (2014) and others as shown in Section 5.2. In addition travel to collaboration meetings at MSU and LLNL by Elster, Eremenko, and Hlophe was supported. The grant also supported travel of Eremenko to the INT and Hlophe to a summer school at ECT* in Trento.

5 Deliverables

5.1 Publications

1. Published paper [45]: Physical Review C 82, 051601(R) (2010)
   Unitary correlation in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors. A. M. Mukhamedzhanov and A. S. Kadyrov.
2. Published paper [49]: Phys. Rev. C 83, 034610 (2011) – Published March 22, 2011
   Improved description of ^{34,36,46}Ar(p,d) transfer reactions, F. M. Nunes, A. Deltuva, and June Hong.
3. Published paper [43]: Phys. Rev. **C 83**, 055805 (2011) – Published May 31, 2011.
   Reexamination of the astrophysical S factor for the $\alpha + d \rightarrow^6$ Li $+ \gamma$ reaction, A. M. Mukhamedzhanov, L. D. Blokhintsev and B. F. Irgaziev.
4. Published paper [37]: Phys. Rev. C 84, 034601 (2011) – Published September 1, 2011
   Direct reaction measurements with a ^{132}Sn radioactive ion beam, K. L. Jones, F. M. Nunes, *et al.*
5. Publishes paper [72]: Phys. Rev. C 84, 035805 (2011) – Published September 14, 2011
   Asymptotic normalization of mirror states and the effect of couplings, L. J. Titus, P. Capel, and F. M. Nunes.
6. Published paper [48]: Phys. Rev. C 84, 034607 (2011) – Published September 19, 2011
   Adiabatic approximation versus exact Faddeev method for (d,p) and (p,d) reactions, F. M. Nunes and A. Deltuva.

7. Published paper [40]: Physical Review **C 84**, 024616 (2011) – Published August 29 , 2011.
Asymptotic normalization coefficients from the ^{14}C(d, p)^{15}C reaction, A.M. Mukhamedzhanov, V. Burjan, M. Gulino, Z. Hons, V. Kroha, M. McCleskey, J. Mrazek, N. Nguyen, F. M. Nunes, S. Piskor, S. Romano, M.A. L. Sergi, C. Spitaleri, and R. E. Tribble.
8. Published paper [15]: The Astrophysical Journal Letters, **739**, L54 (2011) – Published September 9, 2011.
The fluorine destruction in stars: first experimental study of the $^{19}\mathrm{F}(p,\alpha_0)^{16}\mathrm{O}$ reaction at astrophysical energies, M. La Cognata, A. M. Mukhamedzhanov, C. Spitaleri, I. Indelicato, M. Aliotta, V. Burjan, S. Cherubini, A. Coc, M. Gulino, Z. Hons, G. G. Kiss, V. Kroha, L. Lamia, J. Mrazek, S. Palmerini, S. Piskor, R. G. Pizzone, S. M. R. Puglia, G. G. Rapisarda, S. Romano, M. L. Sergi, and A. Tumino.
9. Published paper [10]: Physics Letters B **705**, 112 (2011) – Published September 28, 2011
One-neutron halo structure by the ratio method, P. Capel, R. C. Johnson, F. M. Nunes
10. Published paper [51]: Proceedings CGS14, World Scientific, in press.
Are present reaction theories for studying rare isotopes good enough?, F. M. Nunes, P. Capel, R.J. Charity, A. Deltuva, W.Dickhoff, H. Esbensen, R.C. Johnson, N.B. Nguyen, N.J. Upadhyay, S.J. Waldecker.
11. Published paper [47]: Phys. Rev. C 84, 044611 (2011) – Published October 14, 2011
Transfer reactions and the dispersive optical model, N. B. Nguyen, S. J. Waldecker, F. M. Nunes, R. J. Charity, and W. H. Dickhoff.
12. Published paper [41]: Phys. Rev. C 84, 044616 (2011) – Published October 21, 2011.
Theory of deuteron stripping: From surface integrals to a generalized R-matrix approach, A. M. Mukhamedzhanov.
13. Published paper [34]: Phys. Rev. C 85, 024613, (2012) – Published February 21, 2012.
Utilizing (p,d) and (p,t) reactions to obtain (n,f) cross sections in uranium nuclei via the surrogate-ratio method, R. O. Hughes, C. W. Beausang, T. J. Ross, J. T. Burke, N. D. Scielzo, M. S. Basunia, C. M. Campbell, R. J. Casperson, H. L. Crawford, J. E. Escher, J. Munson, L. W. Phair, and J. J. Ressler.
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Elastic Scattering of ^{6}He based on a Cluster Description, S. P. Weppner and C. Elster.
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18. Published paper [74]: Phys. Rev. C 85, 054621 (2011) – Published May 25, 2012.
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20. Published paper[80]: Phys. Rev. C: **86** 032802 (2012) - Published September 14, 2012
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Low-temperature triple-alpha rate in a full three-body model, N.B. Nguyen, F.M. Nunes, I.J. Thompson and E.F. Brown
22. Published paper [42]: Phys. Rev. C: **86** 044615 (2012) - Published October 15, 2012
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Carlson, D.J. Dean, G.M. Fuller, R.J. Furnstahl, M. Hjorth-Jensen, R.V.F. Janssens, Bao-An Li, W. Nazarewicz, F.M. Nunes, W.E. Ormand, S. Reddy, B.M. Sherrill,

43. Published paper [68]: Nuclear Data Sheets **118**, 298 (2014).
Coupled-channel treatment of Isobaric Analog Resonances in (p,pγ) Capture Processes, I.J. Thompson, and G. Arbanas,
44. Published paper [69]: Nuclear Data Sheets **118**, 292 (2014).
Coupled-Channel Models of Direct-Semidirect Capture via Giant-Dipole Resonances, I.J. Thompson, J.E. Escher, and G. Arbanas.
45. Published paper [26]: Phys. Rev. C. **89**, 054605 (2014)
Reexamining Surface-Integral Formulations for One-Nucleon Transfers to Bound and Resonance States, J.E. Escher, I.J. Thompson, G. Arbanas, Ch. Elster, V. Eremenko, L. Hlophe, F.M. Nunes and N.J. Upadhyay,
46. Published paper [73]: Phys. Rev. C. **89**, 034609 (2014)
Testing the Perey effect, L. Titus and F.M. Nunes,
47. Published paper [33]: Phys. Rev. C. **90**, 014304 (2014)
^{236}Pu(n,f), ^{237}Pu(n,f) and ^{238}Pu(n,f) cross sections deduced from (p,t), (p,d) and (p,p$^?$) surrogate reactions, R.O. Hughes, C.W. Beausang, T. J. Ross, J.T. Burke, R.J. Casperson, N. Cooper, J.E. Escher, K. Gell, E. Good, P. Humby, M. McCleskey, A. Saastimoinen, T.D. Tarlow, and I.J. Thompson,
48. Published paper [79]: Phys. Rev. C **91**, 045802 (2015)
Exploration of direct neutron capture with covariant density functional theory inputs, Shi-Sheng Zhang, Jin-Peng Peng, M. S. Smith, G. Arbanas, and R. L. Kozub
49. Proceedings [20]: *arXiv:1410.1227* (in press)
Separable Optical Potentials for (d,p) Reactions, Ch. Elster, L. Hlophe, V. Eremenko, F.M. Nunes, G. Arbanas, J.E. Escher, I.J. Thompson.
50. Published paper [23]: Comp. Phys. Comm. **187**, 195 (2015)
Coulomb Wave functions in Momentum Space. V. Eremenko, N. Upadhyay, I. Thompson, C. Elster, F. Nunes, G. Arbanas, J. Escher, and L. Hlophe.

5.2 Presentations

1. *Improving the theory for transfer reactions*, Invited talk by F.M. Nunes, INPC July 2011, Vancouver, Canada.
2. *Where did matter come from?*, Colloquium by F.M. Nunes, University of Michigan Dearborn, Dearborn, U.S.A.
3. *Reaction theory for studying rare isotopes: the missing piece of the puzzle*, Colloquium by F.M. Nunes, University of Notre Dame, South Bend, U.S.A.
4. (d,p) *reactions. Simple or complicated*, Invited talk by A.M. Mukhamedzhanov, 7 April 2010 at the ECT* "Reactions and Nucleon Properties in Rare Isotopes", Trento, Italy, April 6-10, 2010.
5. *Unitary correlations in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors*, Invited talk by A.M. Mukhamedzhanov, 22 September 2010 at ATOMKI, Debrecen, Hungary.

6. *Unitary correlations in nuclear reaction theory: Separation of nuclear reactions and spectroscopic factors*, Invited talk by A.M. Mukhamedzhanov, 26 October 2010 at the ECT* "Workshop on Limits of existence of Light Nuclei", Trento, Italy, October 25-30, 2010
7. Goran Arbanas participated in the FUSTIPEN Inauguration and gave the talk "Neutron Matter as a Composite Bose-Fermi Superfluid" the first FUSTIPEN workshop: "Bridging the Atlantic with Exotic Isotope Physics", GANIL, Caen, France (January 18-19, 2011).
8. *Simultaneous and Sequential Contributions to Two-nucleon Transfer Reactions*, Invited talk by I.J. Thompson, November 20, 2010 at the RIKEN workshop "Probing Neutron-Proton Pair Correlations – pairing models, cross section measurements and reaction mechanisms", RIKEN Nishina Center, Japan on November 19-20, 2010
9. *Nuclear Reactions - a Challenge for Few- and Many-Body Theory* Invited talk by Ch. Elster, November 6, 2010 at the "2010 Fall Meeting of the APS Division of Nuclear Physics", Santa Fe, NM, Bulletin of the American Physics Society, Vol. 55, No 14, BAPS.2010.DNP.MC.1
10. *A Nucleon-Nucleus Optical Potential for Rare Isotope Beam Facilities* Contributed talk by Stephen Weppner, November 6, 2010 at the "2010 Fall Meeting of the APS Division of Nuclear Physics", Santa Fe, NM, Bulletin of the American Physics Society, Vol. 55, No 14, BAPS.2010.DNP.MC.6
11. *Some remarks on reaction theory for Rare Isotopes*, Contribution by F.M. Nunes, 19 January at FUSTIPEN inauguration, Caen, France.
12. *Reaction theory for studying rare isotopes: the missing piece of the puzzle*, Colloquium by F.M. Nunes, 24 Feb at Michigan State University, East Lansing, U.S.A.
13. *Cross sections for astrophysics and other applications,* Invited talk by J. E. Escher, LLNL, at the XXXIV Symposium on Nuclear Physics in Cocoyoc, Mexico, January 2011.
14. *Coupled-channels Neutron Reactions on Nuclei*, Invited Seminar by Ian Thompson at the Institute of Nuclear and Particle Physics, Ohio University, Feb 2011.
15. *Reactions with deuterons within the CDCC formalism*, Contributed Talk by Neelam Upadhyay, APS meeting, April 2011.
16. *Nuclear reactions for astrophysics and other applications*, Invited Talk by Jutta Escher, Notre Dame University, March 2011.
17. *Nuclear reactions for astrophysics and other applications*, Invited Talk by Jutta Escher, Argonne National Laboratory, March 2011.
18. *Uncertainties from theory on transfer reactions*, Invited Talk by Filomena Nunes, ECT* Workshop on Transfer and Knockout Reactions, Trento, Italy, May 9, 2011
19. *Compound nucleus production by partial fusion in (d,p) reactions*, Invited Talk by Ian Thompson, ECT* Workshop on Transfer and Knockout Reactions, Trento, Italy, May 13, 2011
20. *Using transfer and inelastic scattering mechanisms to infer compound reaction cross sections*, Invited Talk by Jutta Escher, ECT* Workshop on Transfer and Knockout Reactions, Trento, Italy, May 2011.
21. *Short-range correlations, nuclear reactions and spectroscopic information*, Invited talk by Akram Mukhamedzhanov, ECT* Workshop on Nuclear Many-Body Open Quantum Systems: Continuum and Correlations in Light Nuclei, Trento, Italy, June 6-10, 2011.
22. *Advancing the theory of transfer reactions*, Invited Talk by Filomena Nunes, UNEDF annual meeting, East Lansing, 21st June 2011
23. *The TORUS project*, Invited Talk by Filomena Nunes, FRIB theory workshop, INT, Seattle, 8th August 2011

24. *Theory and Calculation of Two-nucleon Transfer Reactions*, Invited Talk by Ian Thompson, FRIB theory workshop, INT, Seattle, 8th August 2011
25. *Application of Three-Body Methods in Nuclear Reactions:* ^{6}*He(p,p)*^{6}*He*, Inv. Talk, Ch. Elster, INT workshop on 'Interfaces between Nuclear Reactions and Structure', August 8 - September 11, 2011, Seattle, WA.
26. *Are present reaction theories for studying rare isotopes good enough?*, Invited Talk by Filomena Nunes, CGS14, Guelph, 2nd September 2011
27. *Testing formalisms for deuteron breakup and transfer reactions*, Contributed Talk by Neelam Upadhyay, DNP meeting, East Lansing, 28th October 2011.
28. *Elastic Scattering of* ^{6}*He based on a Cluster Description*, Contributed Talk, S.P. Weppner, Ch. Elster, 2011 Fall Meeting of the APS Division of Nuclear Physics, East Lansing, MI, Bulletin of the American Physical Society,
Vol. 56, No 12, BAPS.2011.DNP.JE.2
29. *Microscopic Optical Potentials for the Reaction Helium-6 (p,p) Helium-6*, Invited Talk, Ch. Elster, Mini-workshop on 'Polarization Phenomena in Proton Elastic Scattering from Unstable Nuclei', December 21, 2011, RIKEN, Tokyo, Japan.
30. *Microscopic Optical Potentials for the Reaction Helium-6 (p,p) Helium-6*, Ch. Elster, Seminar, December 2011, RIKEN Nishina Center, Japan.
31. *Lectures on FRIB physics*, Invited Lectures by Filomena Nunes, Lattice QCD summer school, INT, August 2012
32. *Status of reaction theory for studying rare isotopes*, Invited Talk by Filomena Nunes, 13th International conference on Nuclear Reactions Mechanisms, Varenna, 11-15 June 2012
33. *Status of reaction theory for studying rare isotopes*, Invited Talk by Filomena Nunes, HITES, New Orleans, 4-7 June 2012
34. *Status of reaction theory for (d,p) reactions*, Invited Talk by Filomena Nunes, Colloquium at University of Connecticut, 6th April 2012
35. *Reaction theory for exotic nuclei*, Invited Seminar by Neelam Upadhyay, Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai, India May 2012.
36. *Reaction theory for exotic nuclei*, Invited Seminar by Neelam Upadhyay, Centre for Excellence in Basic Sciences, University of Mumbai, Mumbai, India, May 2012.
37. *Comparing CDCC, Faddeev and Adiabatic models*; Talk by Neelam Upadhyay, TORUS Second Year Review, NSCL, Michigan State University, East Lansing, USA, June 2012.
38. INT workshop on 'Structure of Light Nuclei', October 7-12, 2012, Seattle, WA, 'Spin phenomena is elastic scattering of Helium-6 off Protons', Inv. Talk, Ch. Elster
39. 25th Midwest Nuclear Theory Get-Together, Sept. 7-8, 2012, Argonne, IL, 'Towards a Faddeev Description of (d,p) Reactions: Separabilization of Optical Potentials', Ch. Elster, L. Hlophe
40. Horizons of Innovative Theories, Experiments, and Supercomputing in Nuclear Physics (HITES 2012), June 4-7, 2012, New Orleans, LA, *Nuclear Reactions: A Challenge for Few- and Many Body Theories*, Inv. Talk, Ch. Elster, arXiv:1209.0838 [nucl-th], Ch. Elster and L. Hlophe, J. Phys.: Conf. Ser.**403** 012025 (2012).
41. *Theoretical considerations of internal spin for elastic nucleon-nucleus scattering of* ^{6}*He*, 11th Conference on the Intersections of Particle and Nuclear Physics (CIPANP) 2012, May 29-June 3, 2012, St Petersburg, FL, S.P. Weppner, A. Orazbayev, and Ch. Elster.

42. *Polarization Phenomena in the Reaction ^{6}He(p,p)^{6}He*, Annual Meeting of the Ohio Section of APS (OSS12), April 13-14, 2012, Columbus, OH, A. Orazbayev, S.P. Weppner, Ch. Elster.
43. *Exploring R-matrix ideas for the description of one-nucleon transfer reactions*, Jutta Escher, LLNL, May 2012.
44. *Using R-matrix ideas to describe one-nucleon transfers to resonance states*, Jutta Escher, invited talk at the HITES 2012 conference, New Orleans, June 2012.
45. *Status of Reaction Theory for Studying Rare Isotopes*, Filomena Nunes, 13th International Conference on Nuclear Reaction Mechanisms, Varenna, June 2012.
46. *Exploring R-matrix Ideas for the Description of One-nucleon Transfers to Resonance States*, Jutta Escher, DNP 2012 Fall Meeting, Newport Beach, CA, October 2012.
47. *Reaction Theory Developments for Nuclear Astrophysics and Other Applications*, Jutta Escher, Ohio University, November 2012.
48. *Reaction Theory Advances For FRIB*, Ian Thompson, invited talk at the DNP 2012 Fall Meeting, Newport Beach, CA, October 2012.
49. *Theory for Low-Energy Nuclear Reactions*, Invited Lectures by Jutta Escher at the "Exotic Beam Summer School 2013," Lawrence Berkeley National Laboratory, Berkeley, CA, July 29 - August 3, 2013.
50. *Theory for Low-Energy Nuclear Reactions*, Invited Lectures by Jutta Escher at UC Berkeley, Berkeley, CA, November 4 & 6, 2013.
51. *Towards an Improved Understanding of the Formation and Decay of Compound Nuclei*, Invited Conference Talk by Jutta Escher at the *4th International Workshop on Compound-Nuclear Reactions and Related Topics (CNR*13)*, Maresias, Brazil, October 7-11, 2013.
52. *Lectures on Reaction Theory*, Invited Lectures by Filomena Nunes, TALENT course 6, Caen, 1-20 July 2013
53. *Overview of Nuclear Theory*, Invited Talk by Filomena Nunes, Physics of Atomic Nuclei Program, East Lansing, August 2013
54. *Updates on FRIB and FRIB theory*, Invited Talk by Filomena Nunes, NUCLEI collaboration meeting, Bloomington, June 2013
55. *Theoretical developments in the study of deuteron induced reactions*, Invited Talk by Filomena Nunes, Nuclear structure and reactions: EXperimental and Ab-initio theoretical perspectives, 18-21 Feb 2014
56. *Quantifying the limits of the (d,p) reaction theories* Interview Talk by Neelam Upadhyay, National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, 28 February 2013
57. *Coupled-channel treatment of Isobaric Analog Resonances in (p,pγ) Capture Processes*, International Conference on Nuclear Data for Science and Technology, March 4-8, 2013, New York, NY, I.J. Thompson, and G. Arbanas.
58. *Coupled-Channel Models of Direct-Semidirect Capture via Giant-Dipole Resonances*, International Conference on Nuclear Data for Science and Technology, March 4-8, 2013, New York, NY, I.J. Thompson, J.E. Escher, and G. Arbanas.
59. *The (d,p) reaction theories & their limitations* Interview Talk by Neelam Upadhyay, Department of Physics Astronomy, Louisiana State University, Baton Rouge, 8 March 2013
60. *Limitations of (d,p) reaction theory* Talk by Neelam Upadhyay, Stewardship Science Academic Alliance (SSAA) Meeting, Lawrence Livermore National Laboratory, Livermore, 18-19 March 2013

61. *Effect of varying charge and mattter radii on observables in ^{6}He and ^{8}He*,Spring 2013 Meeting of the APS Ohio-Region Section, March 29-30, Athens, Ohio, A. Orazbayev, Ch. Elster, S.P. Weppner.
62. *Separabilization of Optical Potentials in Momentum Space*, Spring 2013 Meeting of the APS Ohio-Region Section, March 29-30, Athens, Ohio, L. Hlophe, Ch. Elster.
63. *Microscopic Optical Potential for Scattering of ^{6}He and ^{8}He off Protons*, APS April Meeting 2013, April 13-16, Denver, CO, Ch. Elster, A. Orazbayev, S.P. Weppner.
64. *Methods for Vertex Integrals of Coulomb Potentials* Talk by Neelam Upadhyay, TORUS Third Year Review, Lawrence Livermore National Laboratory, Livermore, 11-12 June 2013
65. *Towards (d,p) Reactions with Heavy Nuclei in a Faddeev Description*, International Workshop on Nuclear Dynamics with Effective Field Theories, July 1-3. 2013, Bochum, Germany, Inv. Talk, Ch. Elster,
66. *Towards (d,p) Reactions with Heavy Nuclei in a Faddeev Description*, L. Hlophe, Ch. Elster, L. Hlophe, V. Eremenko, N.J Upadhyay, F.M. Nunes, G. Arbanas, J.E. Escher, I.J. Thompson, International Workshop on Nuclear Dynamics with Effective Field Theories, July 1-3. 2013, Bochum, Germany.
67. *Momentum Space Coulomb Distorted Matrix Elements for Heavy Nuclei*, The 22nd European Conference on Few-Body Problems in Physics, September 9-13, 2013, Krakow, Poland, Ch. Elster, V. Eremenko, N.J. Upadhyay, L. Hlophe, F.M. Nunes, G. Arbanas, J.E. Escher, I.J. Thompson.
68. *Coulomb distorted nuclear matrix elements in momentum space: I. Formal aspects*, Annual Meeting of the Division of Nuclear Physics (DNP), October 24-26, Newport News, VA, N.J. Upadhyay, V. Eremenko, L. Hlophe, F.M. Nunes, Ch. Elster.
69. *Coulomb distorted nuclear matrix elements in momentum space: II. Computational Aspect*, Annual Meeting of the Division of Nuclear Physics (DNP), October 24-26, Newport News, VA, V. Eremenko, N.J. Upadhyay, L. Hlophe, Ch. Elster, F.M. Nunes.
70. *The Similarity Renormalization Group for the Three-Body Bound State: A Three-Dimensional Approach*, Annual Meeting of the Division of Nuclear Physics (DNP), October 24-26, Newport News, VA, M. Hadizadeh, K. A. Wendt, Ch. Elster.
71. *Momentum Space Coulomb Distorted Matrix Elements for Heavy Nuclei*,26th Midwest Nuclear Theory Get-Together, Sept. 6-7, 2013, Argonne, IL, V. Eremenko, N.J. Upadhyay, F.M. Nunes, Ch. Elster, L. Hlophe, G. Arbanas, J.E. Escher, I.J. Thompson
72. *A self-consistent coupled-channels method for direct neutron capture on non-spherical nuclei: ^{56}Fe(n,γ)^{57}Fe*, I.J. Thompson, G. Arbanas at NEMEA-7/CIELO International Collaboration on Nuclear Data A workshop of the Collaborative International Evaluated Library Organisation, November 5-8, 2013, Geel, Belgium,
73. *Direct Capture Reactions*, Nuclear Data Week: USNDP/CSEWG/NDAG Meetings, Nov 18-22, 2013, Brookhaven National Laboratory, NY, G. Arbanas, I.J. Thompson, J.E. Escher, F.S. Dietrich.
74. *Spin Phenomena in Elastic Scattering of Helium-6 and Helium-8 off Protons*, Ch. Elster, Notre Dame University, IN, November 2013.
75. *Separable Optical Potentials for (d,p) Reaction Calculations*, Ch. Elster, NSCL, Michigan State University, November 2013.
76. *Spin Phenomena in Elastic Scattering of Helium-6 and Helium-8 off Protons*, Ch. Elster, Iowa State University, Ames, IA, October 2013.

77. *Theoretical developments in the study of deuteron induced reactions*, Invited Talk by Filomena Nunes, Nuclear structure and reactions: EXperimental and Ab-initio theoretical perspectives, TRIUMF, 18-21 Feb 2014
78. *Theory opportunities with Facility for Rare Isotope Beams*, Invited Talk by Filomena Nunes, Colloquium at Colorado School of Mines, March 2014
79. *Spin Phenomena in Elastic Scattering of Helium-6 and Helium-8 off Protons*, Ch. Elster, Pacific University, Khabarovsk, Russia, June 2014.
80. *The Coulomb Problem in Momentum Space without Screening*, Invited Talk, Ch. Elster (for the TORUS Collaboration), Nuclear Theory in the Supercomputing-Era (NTSE-2014), June 23-27, 2014, Khabarovsk, Russia.
81. *Recent reaction theory results and plans*, Invited Talk by Filomena Nunes, Center of Excellence RIBSS retreat, East Lansing, June 2014
82. *Theory of nuclear reactions*, Invited Talk by Filomena Nunes, Exotic Beam Summer School, Oak Ridge, July 2014
83. *Nuclear Reactions: A Challenge for Few- and Many-Body Theory*, Ch. Elster at Louisiana State University, September 2014, .
84. *"Coulomb distorted T-Matrix Elements in Momentum Space"*, Contributed Talk, V. Eremenko, 2014 Annual Fall Meeting of the APS Division of Nuclear Physics," in Waikoloa, HI, Oct 7-11, 2014.
85. *Using R-matrix ideas to describe one-nucleon transfers to resonance states*, presented by Jutta Escher at the "2014 Annual Fall Meeting of the APS Division of Nuclear Physics," in Waikoloa, HI, Oct 7-11, 2014.
86. *Coupled-Channel Computation of Direct Neutron Capture on Non-Spherical Nuclei*, presented by G. Arbanas at the "2014 Annual Fall Meeting of the APS Division of Nuclear Physics," in Waikoloa, HI, Oct 7-11, 2014.
87. *FRIB theory: a broad perspective*, Invited Talk by Filomena Nunes, Colloquium, University of Washington St. Louis, October 2014
88. *Theory opportunities with the Facility for Rare Isotope Beams*, Invited Talk by Filomena Nunes, Western Michigan University, February 2015
89. *Six challenges: reaction theory for heavy unstable nuclei*, Invited Talk by Filomena Nunes, Institute for Nuclear Theory, March 2015
90. *Towards Faddeev-AGS equations in a Coulomb basis in momentum space'*, Contributed Talk by V. Eremenko, INT Workshop on "Reactions and Structure of Exotic Nuclei", March 2-13, 2015, Seattle, WA.
91. *FRESCO: Coupled-channels Calculations*, Inv. Talk by Ian Thompson, INT workshop on "Reactions and Structure of Exotic Nuclei", March 2-13, 2015, Seattle, WA.
92. *Direct, Semi-Direct, and Resonant Neutron Capture*, invited talk by G. Arbanas at the INT 2015 Workshop "Reactions & Structure of Exotic Nuclei," Seattle, WA, March 2015.
93. *Microscopic Folding Potentials and Connections to Structure Description*, Invited Talk by Charlotte Elster, INT workshop on "Reactions and Structure of Exotic Nuclei", March 2-13, 2015, Seattle, WA.
94. *Interplay of direct, pre-equilibrium, and compound processes in nuclear reactions*, invited talk by Jutta Escher, INT 2015 Workshop "Reactions & Structure of Exotic Nuclei," Seattle, WA, March 2015.

95. *Direct, Semi-Direct, and Compound Resonant Neutron Capture*, invited talk by G. Arbanas at the "Galactic evolution, Nuclear Astrophysics and Stellar Hydrodynamics (GNASH) Workshop", University of Victoria Victoria, BC, Canada, May 25 - 29, 2015
96. *Reactions and Decays*, Ian Thompson, Talk at the Center of Excellence RIBSS retreat, Knoxville, June 2015
97. *One nucleon transfer reactions and the optical potential*, Invited Talk by Filomena Nunes, 14th International Conference on Nuclear Reaction Mechanisms, Varenna, Italy, June 2015
98. *Challenges for the description of one-nucleon transfers to resonance states*, Invited Talk by Ian Thompson, 14th International Conference on Nuclear Reaction Mechanisms, Varenna, Italy, June 2015
99. *Coupled-Channel Computation of Direct Neutron Capture and (d,p) reactions on Non-Spherical Nuclei*, Invited talk by Goran Arbanas, 14th International conference on Nuclear Reactions Mechanisms, Varenna, Italy, 2015

5.3 TORUS Workshops

Mini-workshop on Separabilization of Interactions, November 2011

Personnel involved: F. Nunes, Ch. Elster

On November 10 and 11, 2011 a Mini-workshop on the Separabilization of two-body interactions was held at MSU with Prof. Ron Johnson (Surrey), George Rawitscher (U. Connecticut), and Scott Bogner (MSU) as invited guests. In addition postdoctoral researcher N. Upadhyay and graduate students N.B. Nguyen and L. Titus participated in the workshop. During this short workshop the pros and cons of various approaches to representing nucleon-nucleon and nucleon-nucleus interactions by functional approximations, either Sturmian or separable, were discussed.

Mini-workshop on AGS equations and implementations, October 2012

Personnel involved: F. Nunes

On October 18th 2012, a Mini-workshop on AGS equations and implementation, was held at MSU with Deltuva (Lisbon), Elster (Ohio), Hlope (Ohio), Nunes (MSU), Titus (MSU), and Upadhyay (MSU). Discussions included non-local interactions, separabalizing optical potentials, the momentum-space Coulomb distorted representation and details on the AGS equations as implemented by the Lisbon group.

Mini-workshop on EST separable potentials, May 2013

Personnel involved: F. Nunes

Ron Johnson (Surrey) visited Nunes at MSU during May 2013. During that period the group from OU came to MSU for a two day meeting, for discussions on various topics including the work on the EST separable potentials [31].

Annual TORUS Collaboration workshops in June

Our collaboration met annually, usually in June, to hear reports from all our researchers, to discuss physics and plan for the next year. These meetings were at MSU in June of 2010, 2011, 2012; at Livermore Laboratory in 2013, and at MSU again in June 2014.

5.4 Other Workshops

DNP 2012 Workshop 'And Here Be Dragons: Understanding the Nature of Unstable Isotopes'

Personnel involved: J. Escher, I.J. Thompson

Jutta Escher co-organized (with Calvin Johnson, SDSU) this half-day workshop in the context of the DNP 2012 Fall Meeting. The workshop covered phenomena associated with the effects of the continuum in nuclear physics, including reactions with unstable isotopes. Featured speakers included Ian Thompson and Jolie Cizewski who covered, respectively, theoretical and experimental aspects of (d,p) transfer reactions. Approximately 60 scientists attended.

Workshop INT-15-58W 'Reactions and Structure of Exotic Nuclei', March 2015

Personnel involved: I. J. Thompson and Ch. Elster

Two of the PIs on this project were co-organizers (along with Wim Dickhoff) of the workshop on "Reactions and Structure of Exotic Nuclei" held 2-13 March, 2015 at the INT in Seattle. This two-week workshop brought together over 40 members of several distinct communities, represented by their leading experts. The setup in the first week was successful in bringing together members from the theory as well as experimental community, who were able to clearly lay out the challenges which the understanding of reactions with exotic nuclei poses when considering the different mass and energy regions. One of the main purposes of this workshop was to bring structure and reaction theorists together to develop common language, understand issues common to both subfields, as well as establish priorities for future developments. As a unifying element the notion that the study of exotic nuclei requires mostly strongly interacting tools and therefore a simultaneous description of nuclear structure and reactions was emphasized by the many talks presented by experimentalists. The total number of participants was over 35 during the first week with a corresponding number of talks. A smaller group of about 15 was involved in the second week which was devoted to more in depth discussions with only one morning presentation scheduled.

A major conclusion reached by most participants was that workshops like this one are very beneficial to enhance the communication among theorists working on structure and reactions as well as the communication between theorists and experimentalists working on exotic nuclei. Very encouraging is the observation that a common interest in developing a common language in the reaction and structure community emerged from this workshop together with a clearer understanding of the challenges to be addressed in the different mass and energy regimes of reactions of interest at the different experimental facilities.

6 Acknowledgments

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